OPTIMIZATION OF SHAPE ROLLING PROCESSES USING FINITE ELEMENT ANALYSIS AND EXPERIMENTAL DESIGN METHODOLOGY

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Effective design is a prerequisite for quality manufacturing. In the design process, engineers have relied on the use of analytical techniques and, more recently, numerical computer-based tools. Among computational techniques, the finite element method has been successfully applied in the analysis of metal forming operations, particularly rolling. Rolling has been the topic of much research in seeking to understand and quantify the significant parameters that govern this manufacturing process.

The rolling operation consists of two rotating rolls on the same plane, one above the other; a billet is passed through the rotating rolls changing its cross sectional shape and increasing its length (Figure 1). Rolling has been studied using two and three dimensional formulations of the finite element method, with a wide variety of material models, frictional conditions and solutions procedures. However, these sophisticated rolling simulations have not been properly used for the multiobjective parameter design of this manufacturing process. Too often the simulation of a complex rolling operation is combined with trial-and-error or changing one factor-at-a-time techniques to obtain the influence of different inputs on the response.

The purpose of this research is to recognize finite element simulations of rolling operations as the realization of computational experiments, to apply sound experimental design techniques for the analysis and prediction of responses. This research addresses the design of shape rolling processes using optimal parameter
settings for target performance. Although the computer experiments we refer are deterministic (replicate observations at the same inputs are identical), experimental design and data analysis techniques are used assuming the observations are the result of unreplicated fractional factorial designs. The systematic use of experimental design techniques in the analysis of finite element rolling simulations can aid in the design of roll pass and schedules, provide a systematic approach for the analysis of the rolling processes, and improve the quality of rolled products.

Figure 1  Schematic of a Rolling Process
CHAPTER II. Literature Review

Because rolling is a widely used metal forming operation, it has been the topic of much research seeking better understanding of the significant parameters that govern this manufacturing process. With the advent of computers many numerical techniques have been applied to analyzing the rolling process. Numerical models offer a realistic, detailed characterization of the rolling process thus are able to aid effectively in the design of roll pass and scheduling.

In a pioneering work on numerical models, Orowan (1943) developed a graphical method for calculating roll pressure in hot and cold rolling that eliminates previous simplifications of homogeneous compression. Previous works had assumed that roll stock could be divided into thin plane cross sections that remained plane after the rolling operation. Orowan's formulations allowed the implementation of any kind of yield stress and friction variation along the arc of contact. The use of this formulation as a design tool was limited by the number of calculations required to solve a set of complex equations. Another numerical technique which determines the spread, roll torque and neutral points location for plane three-dimensional rolling was introduced in 1975 by Oh and Kobayashi. Their approximation was based on the extremum principle, which required prescribing the geometrical configuration of the deforming body and defining a steady-state velocity field to minimize the total energy rate.

The need to obtain better characterization of rolling processes made
necessary the implementation of more accurate numerical formulations, such as the finite element method. A computer program based on the finite element method was first used by Rao and Kumar (1977) to simulate two-dimensional cold strip rolling. Subsequent finite element analyses of rolling were used to perform sensitivity analyses of dimensions and material properties using the change-one-factor-at-a-time technique (Li and Kobayashi 1982, Liu et al. 1986, Pietrzyk 1986).

Although finite element codes were developed to be auxiliary tools in the design of rolling products and processes, research has mostly focused on the application of different formulations of finite element methods (Bertrand et al. 1986). Bettina (1991) studied the influence of two different friction models, rolling and material parameters on the variation of contact stresses along the roll bite length using the change one-factor-at-a-time technique. There have been some studies which have focused on optimizing the microstructure of rolled products using finite element simulations (Rantanen et al. 1989, Amici et al. 1989).

More recent investigations have focused on the development of specialized finite element packages uniquely designed for three-dimensional simulation of rolling problems (Park and Oh 1990; Mori and Osakada 1989, 1991; Chen and Kobayashi 1990). These codes were developed as an alternative to traditional roll design practices, with the feeling that computer simulators of rolling are desirable tools in the steel industry for designing optimum roll geometry and pass schedule. Other studies include the coupled analysis of the billet and roll deformation (Yanagimoto and Kiuchi 1991, Gratacos et al. 1992). Although most of work
presented in the literature on finite element simulation of rolling is intended to aid in the design of rolling processes, only isolated sensitivity analyses of single parameters significant to the rolling operations have been provided. There is no indication as to how such simulations can be effectively used to obtain a desired die filling, pressure and strain distribution, roll torque and force, or any other output. In most cases researchers imply that trial-and-error and changing one-factor-at-a-time is the normal procedure to follow in using finite element simulations.

There is a need to recognize computer simulations as the realization of computer experimentation for sound statistical analysis of the information obtained. The fact that all of the three-dimensional finite element codes mention above require significant amount of CPU time even for Supercomputers, indicate that a systematic approach is necessary in the selection of inputs and analysis of responses. McKay et al. (1979) pioneered the area of experimental design for deterministic computer models comparing three methods for selecting input variables in the analysis of output from a computer code. These authors proposed the use of Latin hypercube to investigate the propagation of a known input distribution through the output. Iman et al.(1981) proposed a sensitivity analysis also based on Latin hypercube sampling to fit response surfaces and determine the relative importance of input parameters on the response.

Computer codes were studied by Sacks et al. (1989) as a deterministic model (for the same input, the output is identical), where the output was treated
as the realization of an stochastic process to provide a basis for designing experiments and efficient prediction. These results indicate that the main difference between computer and physical experimentation derives from the lack of replication and random error of computer simulations. Logothetis and Wynn (1989) recognized control and measuring of variables as another important difference between computer and physical experiments. This observation is based on the absence of measuring devices that allows careful study of the complexity of the computer model. Regarding the role of statistics in designing computer experiments Sacks et al. (1989) made the following assertions:

- The selection of inputs at which to run a computer code is still an experimental design problem.
- Statistical principles and attitudes to data analysis are helpful however the data is generated.
- There is uncertainty associated with predictions from fitted models, and the quantification of uncertainty is a statistical problem.

Morris (1991) proposed experimental plans for computer models composed of individually randomized one-factor-at-a-time designs. Welch et al. (1990, 1992) also recognized a potential application of experimental design for computer experiments in quality improvement, under the parameter design stage as proposed by Taguchi (1986, 1987). At the parameter design stage significant factors that affect the process are identified and set on the optimal level. The objective of this technique is to reduce the sensitivity of products and processes.
to uncontrollable (noise) factors; thereby making them robust (Kackar, 1985). To account for both mean and deviation, performance parameters called signal-to-noise-ratios are employed in the robust design of products and processes.

Although Taguchi's basic quality philosophy of robust design is generally accepted, his methods of experimental design and data analysis have received much criticism. Box (1989) showed the inadequacy of the signal-to-noise ratios as a measure of location and dispersion, while Montgomery (1991) addressed Taguchi's treatment of interactions and the large number of experiments required by the use of external (noise) orthogonal arrays. In spite of the criticism, Taguchi is recognized for bringing awareness about the need to incorporate experimental design and statistical data analysis techniques into the engineering design process.

Recent investigations have attempted to solve Taguchi's robustness problem using different approaches. Michelena and Agogino (1991) proposed the use of monotonicity analysis to solve the parameter design problem. Otto and Antonsson (1991) presented extensions to the Taguchi Method of product design. Sundaresan et al. (1991) used Taguchi's orthogonal arrays for robust design of gears and beverage cans through the use of simulation programs. A recent panel discussion on Taguchi's parameter design (Nair et al., 1992) presents a comprehensive technical analysis of the contributions and alternatives to this methodology. It also refers to Finite Element Analysis as a potential area for the application of experimental design techniques in the field of deterministic computer
experiments.

The literature review, thus, suggests the need to recognize rolling simulations as a realization of computer experiments and its effective use for optimal parameter design. In addition, there is a need to implement systematic experimental design techniques to effectively aid in making finite element simulation of rolling process an integral design tool in manufacturing.
Planned experimental design techniques were used to conduct and analyze finite element simulations of rolling processes. These techniques were used to select input values at which to run the simulations, identify and rank significant factors, and predict responses to optimize a shape rolling process. The simulation results were validated by selecting initial roll part configuration and processing conditions from the literature. Several roll parameters were identified and varied between two levels using fractional factorials. These parameters were changed to study their influence on the responses, fit linear models and solve the optimization problem.

The set of techniques needed for the optimization of shape rolling have been classified into methods of experimental design and data analysis procedures. Experimental design techniques allowed the selection of proper computational samples for the subsequent data analysis. The selection of these samples determined the number of simulations performed and the strength of the conclusions and predictions for the optimization.

Experimental Design

The experimental design of rolling simulations required the selection of rolling parameters and levels, response variables and suitable experimental
samples. Process knowledge from theoretical understanding and practical experience reported from other researchers was incorporated in the design layout to effectively achieve the experimental objectives for the roll part configuration considered. The selection of rolling parameters was closely related to the analysis of data and was a fundamental step in the experimental design.

Two level fractional factorials were used to collect the simulation results and reduce the number computational runs. Fractional factorials represent a fraction of a full factorial experiment, that is a portion of all the possible factor combinations, and provide an efficient method to estimate main factor effects and some interactions.

Basic Test Strategies

The following example (Ross, 1989) illustrates the use of full and fractional factorials compared to one-factor-at-a-time and several-factors-at-the-same-time test strategies. The strategies are compare in terms of orthogonality and balance. Orthogonality means that the effect of one factor can be evaluated independently from another factor: the effect of one factor does interfere in the estimation of another factor. A balanced experiment has equal number of observations at every level. The example below illustrates this concepts.

Consider an experiment with four controllable factors, represented by the letters A, B, C and D to be varied between two levels each. The low levels are
represented by a minus sign (-) and the high levels by a plus sign (+). Table 1 illustrates the testing sequence for one-factor-at-a-time strategy.

<table>
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<tr>
<th>Trial</th>
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Table 1. One factor-at-a-time test strategy

The first trial run represents the base line condition. The results of trial 2 can only be compared with trial 1 to estimate the effect of factor A in the process performance. The results of trial 3 can only be compared with trial 1 to estimate the effect of factor B, and so on. Every variable is changed one by one while fixing the rest, in hope to achieve the desired response. One of the disadvantages of this technique is that if there is an interaction between two factors it cannot be possibly seen. Furthermore this experiment is neither orthogonal nor balanced.

If all the data under level $A^-$ is averaged and all the data under level $A^+$ is averaged, the comparison between the two levels of A is not balanced. Of all the four trials under level $A^-$, three were at level $B^-$ and one at level $B^+$. The one trial under level $A^+$ was at level $B^-$. Therefore, the effect of factor B on the performance will be confounded with the effect of factor A, and vice versa. Only when trial 1 is
compared to the other trials one at a time, the factor effects are orthogonal.

Table 2 illustrates the several-factors-at-one-time test strategy. This test strategy makes the separation of main factors effects and interactions impossible. This strategy is not orthogonal since there is no way to know if one factor is making a positive contribution and other a negative contribution.

### Table 2. Several Factors-at-a-time strategy

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Table 2. Several Factors-at-a-time strategy

Full factorials are orthogonal and balanced designs that account for all the possible factors combinations, as shown in Table 3. There is an equal number of test data points under each level of each factor. Of the eight data points of level A there are four at B condition and four at the B condition. This same pattern is true for any combination of factors and levels. Because of this balanced arrangement all the main factors effects and their interactions can be estimated, so the experimental design is said to be orthogonal.
A full factorial experiment involving k factors at two levels requires $2 \times 2 \times \ldots \times 2 = 2^k$ observations and is called a $2^k$ full factorial design. In the previous example $k = 4$, so $2^4 = 16$ runs were required. Even for a small number of factors, the total of treatment combinations in a $2^k$ full factorial design is too large for many applications. An alternative is using only a fraction of the full factorial keeping the design orthogonal and balanced; these experiments are called fractional factorials designs. Table 4 illustrates a one-half fraction of the previous $2^4$ full factorial design.

### Table 3. Full Factorial Experiment

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The number of runs have been reduced to $2^{4-1} = 8$ treatment combinations. This reduction is achieved by selecting column $D$ equal to the product of columns $A$, $B$ and $C$ ($D = ABC$). This means that the effect of factor $D$ is confounded with the $ABC$ interaction, so they are said to be aliases. To find the complete alias structure the equation $D = ABC$ is multiplied by $D$ on both sides:

$$D \cdot D = ABC \cdot D$$

$$D^2 = ABCD$$

but multiplying any column by itself will result in the identity column $I$ of plus signs, so

$$I = ABCD$$

is called the *defining relation* of the experimental design. In general, the defining relation is always the set of all columns that are equal to the identity column $I$. The alias of any factor is determined by multiplying that factor by the defining relation.

To find the alias of factor $A$,
\[ A \cdot I = A \cdot ABCD = A^2 BCD \]

since any column multiplied by the identity results in the column itself

\[ A = BCD \]

so the estimated effect of factor A is *confounded* with the three way interaction BCD: the effect of factor A and the interaction BCD will be estimate as single value.

Interactions represent the combined effect of two or more factors. The rest of the alias structure can be found in a similar fashion to be,

\[
\begin{align*}
B &= ACD & AB &= CD \\
C &= ABD & AC &= BD \\
D &= ABC & BC &= AD
\end{align*}
\]

This \(2^{4-1}\) fractional factorial is called a resolution IV design. In general, the resolution of a two level fractional factorial design is equal to the minimum number of letters in any word of the defining relation (in the preceding design \(I = ABCD\), so the resolution is IV). In such a design main effects are not confounded with two way interactions, but two way interactions are confounded with each other.

Fractional factorial designs are classified according to their resolution as follows:

- **Resolution III designs.** These are designs in which no main effects are confounded with any other main effect, but main effects are confounded with two way interactions and two way interactions are confounded with each other.

- **Resolution IV designs.** These are designs in which no main effect is confounded with any other main effect or with any two way interaction, but two way interactions
are confounded with each other.

- Resolution V designs. These are designs in which no main effect or two way interaction is confounded with any other main effect or two way interaction, but two way interactions are confounded with three way interactions.

Both the resolution and the alias structure are essential in the interpretation of the results and determine the strength of the conclusions. The higher the resolution, the less confounding among effects and interactions, but the higher the number of required experiments.

**Data analysis procedures**

The optimization of rolling simulations is based on the use of experimental design data analysis procedures to determine the most influential variables on the response. Using this information a linear model can be fitted to predict the setting of these variables so that the target performance can be obtained. Experimental data analysis provides objectivity to the analysis of results and serves as a decision making tool. Several techniques of data analysis where considered to provide a basis for validation and comparison.

The group of data analysis procedures employed in this research included multiple linear regression modelling, analysis of variance, normal probability plotting, residual analysis, analysis of means as proposed by Length (1989), response surface methodology and the method of the steepest ascent. The
analysis of results from a three-dimensional shape rolling process of the next chapter is intended to illustrate the use of these techniques and their applicability for the optimization of rolling simulations.

It is important to remember that all the data analysis techniques employed here assume that the responses involved in the experimental design have a inherent variability. For the finite element simulations considered in this investigation such variation does not exist. Although this fact contradicts a fundamental assumption of the experimental design analysis, we show that these techniques still provide useful information in the analysis and identification of significant factors. The data analysis is conducted assuming that the responses are the result of an unreplicated two-level fractional factorial design.

The Finite Element Model

The elastic-plastic finite element code ABAQUS was used to conduct simulations of rolling processes. ABAQUS is a commercial multi-purpose finite element code that can be used to simulate metal forming processes. Newton's method is employed as a numerical technique for solving the nonlinear equilibrium equations of the finite element simulations. ABAQUS has an automatic time step increment scheme, based on the maximum force residuals (tolerance PTOL) of each increment to control the convergence rate. This reduces or increases the step increment according to the consecutive values of the residuals. Upper and
lower limits on the step increment can be set by the user, while the force residuals are compared to the selected tolerance for rolling.

This package uses the incremental plasticity theory based on the elastic-plastic material model. Metal plasticity models are based on the Von-Mises yield criteria with isotropic hardening behavior. The Lagragian point of view is used in ABAQUS to record and update material changes and contact conditions as the billet passes through the roll gap. The billet is divided into first order elements with reduced integration and hourglass control for computational economy. Rolls are considered as rigid surfaces, and interface (gap) elements simulate the contact conditions between the billet and the rolls. Frictional conditions are simulated by the standard Coulomb model, with an additional limiting shear stress.

ABAQUS input files are divided into model definition and history definition. The model definition of plane rolling problems includes the mesh, boundary conditions, material properties, rigid surfaces and friction. Because of the symmetry of these problems, only the top half of the problem is modelled and the top roll is defined as a rigid surface. During the history definition, the motion and forces of the model are specified. A pushing die facilitates the insertion of the billet into the roll gap at the beginning of the simulation (Figure 2). The velocity of the pushing die is about one third of the expected velocity of the billet when caught by the rolls. The friction drives the billet into the roll gap and the process is completed.
During the history definition the output desired is also specified. There are four types of output files, according to the extension they have:

- **FIL.** This file contains numeric output requested by the user, such as stresses, strain, displacements and more. It is written in format to be used by other post-processing packages such as PATRAN or ABAQUS post-processor. This file is generated using the *EL FILE and *NODE FILE keywords. It can be either ASCII or Binary.

- **DAT.** This file contains numeric information requested by the user written in readable ASCII characters (table form). It is a report file on the definition of the problem, results and convergence. The numeric information written to this file is controlled by *PRINT, *EL PRINT and *NODE PRINT keywords.

- **RES.** This file contains all the information necessary to restart a simulation. It is

Figure 2  Initial configuration for rolling processes.
used to obtain additional output, change boundary conditions and perform post-processing sessions.

The vectorized version (4.9) of ABAQUS available at the Ohio Supercomputer Center CRAY-YMP8/864 was used to perform the rolling simulations. The connection and transferring of files from Ohio University was made through TELNET and FTP utilities.
Computer Prototypes

The rapid creation of accurate computer prototypes for the simulation of different rolling experiments was a major difficulty faced in this investigation. The creation of a rapid prototyping tool that could generate complex Finite Element Models for different parameter settings became a necessity. An AutoLISP/FORTRAN program for the generation of ABAQUS input files was created to solve this problem.

The first part of this program operates from the AutoCAD environment to extract the coordinates of the top and bottom roll drawings. This code (CORTEMP.LSP, Appendix A1) is written in AutoLISP language and creates standard ASCII files (TOP.DAT and BOT.DAT) of the rolls coordinates that are used in the second module of the prototyping software. The second module (QS_ABQ.FOR, Appendix A2) is a FORTRAN program that reads the coordinate files and requires interactive input from the user to create the ABAQUS input file. This module generates a complete Finite Element Model including the geometry, mesh, boundary conditions, tolerances and time step.

This module is basically divided into three parts contained in the main program. The sequence for input information is as follows:

- Roll Parameters. These are the physical parameters that affect a three dimensional rolling process. Roll parameters are the following: roll radius, roll

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1 AutoCAD and AutoLISP are registered trademarks of Autodesk, Inc.
speed, initial stock size, initial stock width, initial billet length, friction factor, and material type. The properties of different materials are stored in additional files (with .MAT extension) to avoid user mistakes. This file contains the modulus of elasticity, poisson's ratio, the strength coefficient K and the strain hardening coefficient n of the material.

- Simulation Parameters. These parameters control the mesh size by setting the number of layers on each direction, rigid surfaces node numbers and ABAQUS file and plot format (binary or ASCII). Although simulation parameters may affect ABAQUS results they are not related to the physical problem of rolling. Default values are set to all simulation parameters inside the prototyping program.

- Model History Parameters. These parameters control the billet length to be rolled and the convergence of the finite element simulation. They include the maximum number of increments (steps) allowed, the billet length percentage to be rolled, the initial and minimum time increment. The setting the residual tolerance PTOL is particularly critical for the convergence and is set a default value based on approximated equations of roll force and past experience on rolling simulations.

- Post-processing Parameters. This set of parameters control the printing frequency of the simulation results to the RES, DAT and FIL ABAQUS files.
CHAPTER IV. Results

Plain Strain Rolling

Flat rolling was studied using a two dimensional plain strain simulation to compare results with experimental values (Al-Salehi et al. 1973) and other finite element simulations (Park and Oh 1990). The configuration of this case study was the following:

- Roll diameter = 158.75 mm
- Roll speed = 19.2 RPM
- Billet thickness = 6.274 mm
- Roll gap = 5.385 mm
- Reduction = 14.17 %
- Billet length = 25.0 mm
- Friction factor = 0.1
- Poisson's ratio = 0.33
- Young Modulus = 730.84 Gpa

The billet was made of aluminum and the flow stress was given by:

$$\frac{\tau}{\sigma} = 50.3 \left( 1 + \frac{e}{0.05} \right)^{0.26}$$  \[1\]
The mesh was divided in 50 layers along the billet length (x direction) and 5 layers along the thickness direction (y direction), for a total of 250 elements and 314 nodes. Bilinear plain-strain CPE4R elements were used in this simulation. This is a four noded quadrilateral element with one integration point and hourglass control. This element is chosen because it is relatively inexpensive for problems involving nonlinear constitutive behavior, since the material calculations are done at only one point of each element.

Interface elements IRS21 were attached along the top surface of the billet to account for the friction. Figure 3 shows the sequence of steps followed in the simulation. The billet was initially in contact with the top roll, the push die moved forward until the friction forces pull the billet into the roll gap. The billet separates from the push die and the process is stopped once steady state is reached. Figure 4 shows contours of Von Mises stresses and plastic equivalent strain at steady-state condition. The output is compared in terms of the roll force, torque, and pressure distribution along the arc of contact in figures 5, 6 and 7 respectively.
Figure 3  Plain Strain Rolling. Simulation steps.

Figure 4  Plain strain rolling contours
Figure 5  Roll Force. Plain Strain Rolling.

Figure 6  Roll Torque. Plain Strain Rolling.
Figure 7  Pressure Distribution. Plain Strain Rolling
Oval Shape Rolling

Three-dimensional oval shape rolling simulations were conducted to maximize the percentage of die filling in a single rolling pass. This optimization was performed by setting a target cross-sectional geometry represented by the empty space between the rolls (Figure 8). Rolling process parameters were changed between two levels according to Table 5. Case study No. 5a is similar to the configuration presented by Park and Oh, 1990.

Because of the symmetry of the problem only one quarter of the billet was modelled for the simulations. The quarter of the billet was evenly divided into forty layers along the rolling direction and twenty-five elements for each cross section. A total of 1000 C3D8R brick elements and 1476 nodes were used in each simulation. This element is eight noded, with linear displacement, reduced integration and hourglass control. As in the plain-strain rolling simulation, this element selection is taken for computational economy.

Interface elements IRS13 were attached at the top surface and free side of the billet to account for contact conditions. This basic configuration was the same for all the case studies considered.
Material properties of Table 6 were taken from Altan et al. 1983. The billets are rolled at room temperature (68° F) from annealed condition. The flow stress behavior in terms of the plastic strain is given by:
Both steels have the same modulus of elasticity and Poisson's ratio:

\[ E = 210 \text{ Gpa} \]
\[ v = 0.3 \]

<table>
<thead>
<tr>
<th>Material</th>
<th>Strength Coeff. K [Mpa]</th>
<th>Strain Hardening n</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI1020</td>
<td>745.32</td>
<td>0.20</td>
</tr>
<tr>
<td>AISI1045</td>
<td>1019.70</td>
<td>0.11</td>
</tr>
</tbody>
</table>

**Table 6.** Material Flow stress coefficients

A \( 2_{III}^{5-2} = 2^3 \) fractional factorial was run and the die fill percentage and plastic equivalent strain recorded, under steady state conditions, according to Table 7.

<table>
<thead>
<tr>
<th>Run</th>
<th>R</th>
<th>W</th>
<th>T</th>
<th>M</th>
<th>F</th>
<th>% Fill</th>
<th>Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>80.69</td>
<td>0.539</td>
</tr>
<tr>
<td>2a</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>79.64</td>
<td>0.485</td>
</tr>
<tr>
<td>3a</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>87.35</td>
<td>0.598</td>
</tr>
<tr>
<td>4a</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>87.57</td>
<td>0.606</td>
</tr>
<tr>
<td>5a</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>81.45</td>
<td>0.614</td>
</tr>
<tr>
<td>6a</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>80.93</td>
<td>0.569</td>
</tr>
<tr>
<td>7a</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>88.15</td>
<td>0.654</td>
</tr>
<tr>
<td>8a</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>88.96</td>
<td>0.675</td>
</tr>
</tbody>
</table>

**Table 7** Die fill % and plastic equivalent strain responses for a \( 2_{III}^{5-2} \) Fractional Factorial Design.
This fractional factorial design is a resolution III design where columns M and F are the product of two other columns:

\[ M = RW \]
\[ F = RT \]

So the defining relation of this experimental design is:

\[ I = RWM = FRT \]

The complete alias structure is given below:

\[ R = WM + TF \]
\[ W = RM \]
\[ T = RF \]
\[ M = RW \]
\[ F = RT \]
\[ WT = MF \]
\[ RWT = WF + TM \]

This experimental design selection has main effects and two way interactions confounded with each other and is intended to serve as an screening experiment. This type of designs are used to obtain an economic estimation of the significant factors with a minimum number of runs. A summary of steady state values of roll force, torque and maximum Von Mises stresses for cases 1a to 8a was also recorded, and is shown in Table 8. Table 9 is a summary of the computational resources needed for cases 1a to 8a.
Table 8. Summary of steady state values for cases 1a to 8a

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>8.81</td>
<td>5.5898</td>
<td>7332</td>
</tr>
<tr>
<td>2a</td>
<td>6.00</td>
<td>3.7310</td>
<td>5607</td>
</tr>
<tr>
<td>3a</td>
<td>6.26</td>
<td>4.4918</td>
<td>6859</td>
</tr>
<tr>
<td>4a</td>
<td>8.96</td>
<td>8.1313</td>
<td>13896</td>
</tr>
<tr>
<td>5a</td>
<td>8.95</td>
<td>7.9041</td>
<td>12817</td>
</tr>
<tr>
<td>6a</td>
<td>6.21</td>
<td>5.6047</td>
<td>9978</td>
</tr>
<tr>
<td>7a</td>
<td>6.37</td>
<td>6.2863</td>
<td>10770</td>
</tr>
<tr>
<td>8a</td>
<td>9.09</td>
<td>10.925</td>
<td>21406</td>
</tr>
</tbody>
</table>

Table 9. Computational resources and convergence for cases 1a to 8a

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Increments</th>
<th>Iterations</th>
<th>CPU time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>144</td>
<td>611</td>
<td>3151.511</td>
</tr>
<tr>
<td>2a</td>
<td>191</td>
<td>814</td>
<td>4180.520</td>
</tr>
<tr>
<td>3a</td>
<td>195</td>
<td>807</td>
<td>4146.497</td>
</tr>
<tr>
<td>4a</td>
<td>170</td>
<td>705</td>
<td>3856.226</td>
</tr>
<tr>
<td>5a</td>
<td>157</td>
<td>635</td>
<td>3326.818</td>
</tr>
<tr>
<td>6a</td>
<td>226</td>
<td>935</td>
<td>4960.073</td>
</tr>
<tr>
<td>7a</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8a</td>
<td>191</td>
<td>814</td>
<td>4223.056</td>
</tr>
</tbody>
</table>

The computational resources for case 7a are not reported because this simulation was stopped for post processing and then restarted again. For this case the number of iterations and CPU time would seem high compared to the rest of the cases.
Figure 9 shows the sequence of deformation for case study 5a. Figure 10 shows a close-up of the deformed shape and Figure 11 displays the equivalent plastic strain contours at steady state conditions for case study 5a.
Figure 10  Deformed shape under steady state conditions. Case study No. 5a

Figure 11  Case study No. 5. Contour plots
Estimated effects were calculated from Table 7 by Yates Algorithm for the
die fill percentage. Table 10 shows these estimates percentages in descending
order.

<table>
<thead>
<tr>
<th>Order (j)</th>
<th>Factor</th>
<th>Estimated Contrasts</th>
<th>(j-0.5)/7</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>W + RM</td>
<td>7.3300</td>
<td>0.9286</td>
</tr>
<tr>
<td>6</td>
<td>T + RF</td>
<td>1.0600</td>
<td>0.7857</td>
</tr>
<tr>
<td>5</td>
<td>M + RW</td>
<td>0.65</td>
<td>0.62429</td>
</tr>
<tr>
<td>4</td>
<td>F + RT</td>
<td>0.2800</td>
<td>0.50000</td>
</tr>
<tr>
<td>3</td>
<td>WT + MF</td>
<td>0.0350</td>
<td>0.3571</td>
</tr>
<tr>
<td>2</td>
<td>RWT + WF + TM</td>
<td>0.015</td>
<td>0.2143</td>
</tr>
<tr>
<td>1</td>
<td>R + WM + TF</td>
<td>-0.1350</td>
<td>0.0714</td>
</tr>
</tbody>
</table>

Table 10. Estimated contrasts for die fill percentage

The normal probability plots of these effects is shown in Figure 12. All the
effects that lie along the line are considered to be negligible. Looking at the
departures from linearity on a probability plot of estimated effects is a simple
graphical way to identify significant factors and interactions. If we assume two way
interactions are not significant, this first analysis indicates that width W, and
thickness T are important effects.
Another method to estimated factor significance was proposed by Length 1989. Estimated effects are displayed graphically in an analysis-of-means type plot. To reference lines are set at the margin of error (ME) and the simultaneous margin of error (SME). The rationale for these lines is that if none of the contrasts is active, there is a 5% chance that any one contrast will be outside $\pm$ ME and a 5% chance that at least one contrasts will be outside $\pm$ SME. Therefore, an estimated contrast that crosses SME is considered to be active. Factor effects inside ME are considered inactive, and contrasts that lie between ME and SME are uncertain for this analysis. Figure 13 shows the width as an active factor of this experiment while the significance of the thickness on the die fill percentage is uncertain.
Margin of Error for a Contrast (approximate 95% confidence) = .76140
Simultaneous Margin of Error = 1.82453

\[
-7.3 -5.9 -4.4 -2.9 -1.5 .0 1.5 2.9 4.4 5.9 7.3
\]

\[
\begin{array}{c|c|c}
\text{R + WM + TF} & \cdot & \cdot \\
\text{W + RM} & \cdot & \cdot \\
\text{M + RW} & \cdot & \cdot \\
\text{T + RF} & \cdot & \cdot \\
\text{F + RT} & \cdot & \cdot \\
\text{WT + MF} & \cdot & \cdot \\
\text{RWT + WF + TM} & \cdot & \cdot \\
\end{array}
\]

**Figure 13.** Analysis of means for the die fill percentage

An analysis of variance on the die fill experiment can be performed neglecting the contribution of small effects. This technique is applied assuming that the contribution of these effects is comparable to experimental error of the design.

To begin the analysis of variance for unreplicated designs, we need to specify which effects should be used as calculated by the Yates Algorithm, and which should be set to zero. From the information of the normal probability plot and the analysis-of-means plot all factors effects are set to zero, except for W, T and M. Table 11 shows the analysis of variance for this selection.

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Square</th>
<th>Fo</th>
</tr>
</thead>
<tbody>
<tr>
<td>W + RM</td>
<td>107.46</td>
<td>1</td>
<td>107.46</td>
<td>2191.34 @</td>
</tr>
<tr>
<td>M + RW</td>
<td>.84</td>
<td>1</td>
<td>.84</td>
<td>17.23</td>
</tr>
<tr>
<td>T + RF</td>
<td>2.25</td>
<td>1</td>
<td>2.25</td>
<td>45.83 @</td>
</tr>
<tr>
<td>ERROR</td>
<td>.20</td>
<td>4</td>
<td>.05</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>110.75</td>
<td>7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

@ -->Factor significant 1 % level

**Table 11.** Analysis of Variance for the percentage of die fill
From the previous analysis a linear model can be fitted as shown in equation 3:

$$\bar{Y} = 84.3425 + \left(\frac{7.33}{2}\right) * X_w + \left(\frac{-1.06}{2}\right) * X_t + \left(\frac{0.65}{2}\right) * X_m$$  \[3\]

where 84.3425 is the average response and the coded variables $X_w$, $X_t$ and $X_m$ take on the values +1 or -1. So for case study 1a on Table 7 the predicted run value is:

$$\bar{Y} = 84.3425 + \left(\frac{7.33}{2}\right) * (-1) + \left(\frac{-1.06}{2}\right) * (-1) + \left(\frac{0.65}{2}\right) * (+1) = 80.4725$$  \[4\]

Since the observed value is 80.69, the residual is $e = y - \hat{y} = 80.69 - 80.4725 = 0.2175$. The values of $y$, $\hat{y}$ and $e = y - \hat{y}$ for the die fill responses are shown in Table 12.

<table>
<thead>
<tr>
<th>Case Study</th>
<th>$y$</th>
<th>$\hat{y}$</th>
<th>$e = y - \hat{y}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>80.69</td>
<td>80.4725</td>
<td>0.2175</td>
</tr>
<tr>
<td>2a</td>
<td>79.64</td>
<td>79.8225</td>
<td>-0.1825</td>
</tr>
<tr>
<td>3a</td>
<td>87.35</td>
<td>87.1525</td>
<td>0.1975</td>
</tr>
<tr>
<td>4a</td>
<td>87.57</td>
<td>87.8025</td>
<td>-0.2325</td>
</tr>
<tr>
<td>5a</td>
<td>81.45</td>
<td>81.5325</td>
<td>-0.0825</td>
</tr>
<tr>
<td>6a</td>
<td>80.93</td>
<td>80.8825</td>
<td>0.0475</td>
</tr>
<tr>
<td>7a</td>
<td>88.15</td>
<td>88.2125</td>
<td>-0.0625</td>
</tr>
<tr>
<td>8a</td>
<td>88.96</td>
<td>88.8625</td>
<td>0.0975</td>
</tr>
</tbody>
</table>

Table 12. Residuals for the die fill percentage fitted response
These residuals are plotted against the fitted responses from equation 3 on Figure 14. The fitted model appears to be adequate since these residuals show a "patternless" structure. A normal plot of the residuals should be reasonably linear as shown in Figure 15.

Figure 14 Plot of Residuals versus Predicted Value from eq. 3
A similar analysis can be carried out for the equivalent plastic strain response. Table 13 shows these estimated contrasts in descending order.

<table>
<thead>
<tr>
<th>Order (j)</th>
<th>Factor</th>
<th>Estimated Contrasts</th>
<th>(j-0.5)/7</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>W + RM</td>
<td>0.0815</td>
<td>0.9286</td>
</tr>
<tr>
<td>6</td>
<td>T + RF</td>
<td>0.0710</td>
<td>0.7857</td>
</tr>
<tr>
<td>5</td>
<td>M + RW</td>
<td>0.0320</td>
<td>0.62429</td>
</tr>
<tr>
<td>4</td>
<td>F + RT</td>
<td>0.0055</td>
<td>0.50000</td>
</tr>
<tr>
<td>3</td>
<td>RWT + WF + TM</td>
<td>0.0010</td>
<td>0.3571</td>
</tr>
<tr>
<td>2</td>
<td>WT + MF</td>
<td>-0.0085</td>
<td>0.2143</td>
</tr>
<tr>
<td>1</td>
<td>R + WM + TF</td>
<td>-0.0175</td>
<td>0.0714</td>
</tr>
</tbody>
</table>

Table 13. Estimated contrasts for plastic equivalent strain
The normal probability plots of these effects is shown in Figure 16. All the effects that lie along the line are considered to be negligible. This analysis indicates that width $W$, and thickness $T$ and $M$ are important effects.

Since the material has a significant contribution on the plastic strain response, the low level (-) (AISI1020) material type is selected in subsequent simulations. This selection is indifferent for the die fill response but has significant effect on the reduction of the plastic strain. From the previous analysis, a linear model can be constructed using the billet width and billet thickness as the only...
two significant variables. The coefficients for this linear model are obtained dividing by two the effects of the factors calculated by Yates Algorithm:

\[ \bar{Y}_r = 84.3425 + 3.665 \times X_w + 0.53 \times X_t \]  \[5\]

where \( X_w \) and \( X_t \) are coded variables for the billet width and thickness to the \((-1, 1)\) interval. For the width we have a range of \((50.8, 57.15)\) mm so:

\[ X_w = \frac{W - 53.975}{3.175} \]  \[6\]

The thickness interval is \((45.72, 50.8)\) mm so:

\[ X_t = \frac{T - 48.26}{2.54} \]  \[7\]

To apply the method of the steepest ascent using the response surface represented by Equation 5, we move away from the design center \((X_w=0, X_t=0)\) along the path of the steepest ascent. We then move 3.665 units of \( X_w \) for every 0.53 units of \( X_t \), thus the path of the steepest ascent passes through \( X_w=0, X_t=0 \) and has a slope of 0.53/3.665.

A step increment of 2 mm is taken in the width direction, this equivalent to:

\[ \Delta X_w = \frac{\Delta W}{3.175} = \frac{2}{3.175} = 0.6299 \]  \[8\]

therefore:
\[ \Delta X_t = \frac{0.53 \times \Delta X_w}{3.665} = 0.0911 \]  

[9]

In terms of the natural variables the increment in thickness would be:

\[ \Delta T = 2.54 \times \Delta X_t = 0.2314 \]  

[10]

The computed results versus the prediction from the linear models are shown in Table 14. The method of the steepest ascent used in this experiment is illustrated graphically on Figure 17. The non-significant variables were set as flows:

Roll radius = 101.6 mm

Material = AISI1020

Friction = 0.8
Figure 17  First-order response surface and path of the steepest ascent

<table>
<thead>
<tr>
<th>Case</th>
<th>Steps</th>
<th>$X_w$</th>
<th>$X_t$</th>
<th>W [mm]</th>
<th>T [mm]</th>
<th>Fill % eq. 3</th>
<th>Fill % FEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1b</td>
<td>0*Δ</td>
<td>0</td>
<td>0.0</td>
<td>53.975</td>
<td>48.260</td>
<td>84.34</td>
<td>84.66</td>
</tr>
<tr>
<td>2b</td>
<td>1*Δ</td>
<td>0.6299</td>
<td>0.0911</td>
<td>55.975</td>
<td>48.491</td>
<td>86.70</td>
<td>86.91</td>
</tr>
<tr>
<td>3b</td>
<td>2*Δ</td>
<td>1.2598</td>
<td>0.1822</td>
<td>57.975</td>
<td>48.723</td>
<td>89.06</td>
<td>89.39</td>
</tr>
<tr>
<td>4b</td>
<td>3*Δ</td>
<td>1.8897</td>
<td>0.2733</td>
<td>59.975</td>
<td>48.954</td>
<td>91.41</td>
<td>91.33</td>
</tr>
<tr>
<td>5b</td>
<td>4*Δ</td>
<td>2.5196</td>
<td>0.3644</td>
<td>61.975</td>
<td>49.186</td>
<td>93.77</td>
<td>--</td>
</tr>
<tr>
<td>6b</td>
<td>5*Δ</td>
<td>3.1495</td>
<td>0.4555</td>
<td>63.975</td>
<td>49.417</td>
<td>96.13</td>
<td>--</td>
</tr>
<tr>
<td>7b</td>
<td>6*Δ</td>
<td>3.7794</td>
<td>0.5466</td>
<td>65.975</td>
<td>49.648</td>
<td>98.48</td>
<td>--</td>
</tr>
<tr>
<td>8b</td>
<td>7*Δ</td>
<td>4.4093</td>
<td>0.6377</td>
<td>67.975</td>
<td>49.880</td>
<td>100.84</td>
<td>97.39</td>
</tr>
</tbody>
</table>

Table 14. Steepest ascent experiment for die fill percentage
Figure 18 shows the billet deformation for cases studies 2a and 8a, which represent the worst and best case respectively. Figure 19 shows a comparison of die fill for cases 5a (original configuration) and the best case obtained at run 8b (Appendix B2). Figure 20 shows the deformed shape of the billet for case 8b.
Figure 18  Billet deformation for cases 2a and 8a (dark hatch). One quarter of the billet is shown.

Figure 19  Cross sections for cases 5a and 8b (dark hatch)
Figure 20  Deformed Shape for case study 8b.
CHAPTER V. Discussion of Results

Plain Strain Rolling

Figures 5, 6 and 7 compares the roll force, torque and pressure distribution along the arc of contact. The steady state values of roll force and torque are found to be in excellent agreement with previous simulations (Park and Oh 1990). Both roll and torque increase to until a steady state is reached and then become stationary. The fluctuation of values is due to the separation and touching of nodal points as they enter in the roll gap. This fluctuation can be reduced refining the mesh at the expense of computer time. The steady state condition is confirmed by the regular pattern of the equivalent plastic strain contours (Figure 4).

Figure 7 displays the pressure distribution along the arc of contact showing double peaks, which is consistent with experimental observations. The ABAQUS input file used for this simulation is listed in the Appendix B1. About 25 minutes were required to complete this simulation compared with 14 hours of CPU time on a VAX-11/750 reported by Park and Oh. This simulation served to confirm the applicability of ABAQUS to rolling problems and as a learning experience.

Oval Shape Rolling

The results obtained from the combined use of experimental design techniques and finite element analysis of rolling processes are encouraging. Using
a systematic approach we were able study the influence of five factors in eight runs to obtain an initial gain in die fill of 7.5% (case 5a to case 8a). According to the experimental design analysis, roll radius, friction and steel type played a minor roll in the percentage of die filling. We believe this is safe assumption considering the two-way interactions were not significant.

This conclusion is confirmed by the analysis of variance, the normal probability plot of the effects and the analysis of means (Table 11, Figures 12 and 13). According to the residual analysis, significant parameters were correctly identified. A normal probability plots of the residuals lie reasonably well on a straight line. This means that the residuals are normally distributed for the fitted model.

The non-significant factors were set at the most convenient levels to reduce the maximum plastic equivalent strain. Further optimization was obtained by using the method of the steepest ascent. Four trials were made outside of the original design space were the prediction of die fill from the linear model, and the real values from the simulation were off by less than 0.4 % in die fill. This further confirms the correct identification of significant parameters and the adequacy of the linear model.

A final simulation was conducted at 7*Δ (deltas) from the origin of the design space. This simulation had to be conducted in two passes, since the billet was suffering sudden deformation and the convergence of the simulation was too slow. At this point we obtained an additional 15.8 % die fill comparing cases 5a
and 8b. This only represents a 3.5% deviation from the prediction of the linear model fitted at the original design space.
CHAPTER VI. Conclusions and Recommendations

The use of planned experimental design techniques was proven to be an effective tool for reducing the number of computational experiments and identifying significant parameters. Although the theoretical validity of the experimental design techniques employed cannot be proved for deterministic models, the application of a systematic approach for the optimization of shape rolling processes was shown to be useful. The use of fractional factorial designs can be justified as an efficient technique to collect data and fit a linear model. All the stages of the experimental analysis should be conducted combining the best engineering process knowledge and practical experience. Statistical techniques should serve as a decision making tool and provide objectivity to the conclusions.

There is a need for new statistical techniques specially designed for the analysis of deterministic computer models. Different techniques should be implemented according to the complexity and cost of the computer simulation. As exposed in the Literature Review, the area of statistically designed computer models has gained momentum in last years. The computer model itself should also be adapted to different levels of accuracy as the researcher progresses in the design process. The accuracy of the model can also be studied as an optimization problem by setting the internal tolerances properly according to time and accuracy constrains. The most accurate computer models should be used at latter stages of the design.
This study depended heavily on the creation and evaluation of computer models through rapid prototyping programs. These programs were crucial for the generation of accurate and complete simulations models for different parameter settings. As computer models become more complex the use of rapid computer prototyping tools becomes a necessity. One possibility is to use these prototyping programs to include variation to the input parameters of each computer model. This approach can be used to avoid the problems related to the analysis of deterministic computer simulations. It could also be used to perform robust optimization with respect to noise factors.

Another application of statistical techniques to rolling processes is possible through the use of mixture experiment theory. This sampling technique is similar to fractional factorials with the difference that the parameters involved cannot be varied independently. In mixture experiments the ingredients of the mixture have to add up to 100%. For example, if \( x_1, x_2, \ldots, x_n \) denote the proportions of \( p \) components of a mixture, then

\[
0 \leq x_i \leq 1.0 \quad i = 1, 2, \ldots, n
\]

and

\[
x_1 + x_2 + \ldots + x_p = 1
\]

A similar situation is encountered in rolling in the selection of the number of passes for a part configuration, where the total distance to travel is known a priori. The number of passes and the reduction of each pass is known to affect critical variables as the strain and die fill. These applications are left as future work.
BIBLIOGRAPHY


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Appendix A1. AutoLISP Programs

; Program Cortemp. This program extracts the coordinates of the top
; and bottom rolls. It creates two standard files TOP.DAT and BOT.DAT
(defun C:COR (/ prmpt frst bpt tbdata ents lnname a aa b L y lchk count m n vtsa
vtea fn1)
  (setq frst t
    bpt (getvar "INSBASE")
  );
  (command "UNDO" "MARK")
  (setq os (getvar "osmode"))
  (setq anbu os)
  (setq "osmode" 512)
  (command "LAYER" "NEW" "OUETC" "")
    (setq ents (ssget "X" (list (cons 8 "OUETC"))))
    (if ents
      (command "ERASE" ents "")
    )
  (setq ptn (getpoint "Pick a line on the Top Roll"))
  (command "EXPLODE" ptn "")
  (prompt "Ready to process the shapes......")
  (prompt "Enclose the top roll within a window ")
  (setq "OSMODE" 000)
  (setq a (ssget "w" (setq crnpoint (getpoint)) (getcorner crnpoint)))
  (setq "OSMODE" os)
  (command "REDRAW")
  (command "CHANGE" a "" "PROP" "LAYER" "OUETC" "")
  (command "LAYER" "SET" "OUETC" "")
  (command "LAYER" "OFF" "")
  (command "LAYER" "ON" "OUETC" "")
  (command "PEDIT" ptn "J" a "")
  (command "EXPLODE" ptn "")
  (setq n 0)
  (setq m 0)
  (while
    (setq tbdata (tblnext "LAYER" frst))
    (setq m (1 + n))
    (setq n m)
    (setq frst nil)
  )
(setq frst t
     bpt (getvar "INSBASE")
);
(prompt "\nInitializing the Database......Done")
(prompt "\nProcessing the entity......Please do not interrupt")
(setq count 0)
(repeat n
   (setq tbdata (tblnext "LAYER" frst))
   (setq aa (cadr tbdata))
   (setq b (cdr aa))
   (setq lchk (/= b "OUETC"))
   (setq ents (ssget "X" (list (cons 8 b))))
   (if ents
      (if lchk
         (command "ERASE" ents "")
      )
   )
   (setq ents nil)
   (setq frst nil)
)
(setq b (sslength a))
(setq x 1)
(setq more 0)
(prompt "\nProcessing the data........")
(setq fn1 (open "topp.dat" "w"))
(setq ent (entnext))
(setq en (entget ent))
(redraw ent 3)
(setq vtn (cdr (assoc 0 en)))
(setq vtx (cdr (assoc 10 en)))
(setq vty (cdr (assoc 11 en)))
(setq vtr (cdr (assoc 40 en)))
(setq vtsa (cdr (assoc 50 en)))
(setq vtea (cdr (assoc 51 en)))
(if vtr
   (print vtr fn1)
   (print 0.0 fn1)
)
   (print vtx fn1)
   (if vtr
      (print vtsa fn1)
   )
   (if vtr
      (print vtea fn1)
   )
(if vty
  (print vty fn1)
)
(if (= b 1)
  (setq more nil)
)
(while more
  (setq x (+ x 1))
  (if (= x b)
      (setq more nil)
    )
  (setq ent (entnext ent))
  (setq en (entget ent))
  (command "DELAY" 100)
  (redraw ent 3)
  (setq vtn (cdr (assoc 0 en)))
  (setq vtx (cdr (assoc 10 en)))
  (setq vtr (cdr (assoc 40 en)))
  (setq vty (cdr (assoc 11 en)))
  (setq vtsa (cdr (assoc 50 en)))
  (setq vtea (cdr (assoc 51 en)))
  (if vtr
      (print vtr fn1)
      (print 0.0 fn1)
    )
  (print vtx fn1)
  (if vtr
      (print vtsa fn1)
    )
  (if vtr
      (print vtea fn1)
    )
  (if vty
      (print vty fn1)
      (print 0.0 fn1)
    )
)
(close fn1)
(command "REDRAW")
(command "UNDO" "END")
(prompt "Please wait........")
(command "UNDO" "BACK" "")
I : Now for the final shape

(prompt "\Processing completed for the Top Roll.....")
(prompt "\--------------------------")
(setq frst t
    bpt (getvar "INSBASE")
)
(command "UNDO" "MARK")
(setq os (getvar "osmode"))
(setq anbu os)
(setq "osmode" 512)
(command "LAYER" "NEW" "OUETC" "")
(setq ents (ssget "X" (list (cons 8 "OUETC"))))
(if ents
    (command "ERASE" ents "")
)
(setq ptn (getpoint "\Pick a line on the Bottom Roll"))
(command "EXPLODE" ptn "")
(prompt "\nReady to process the shape.....")
(prompt "\nEnclose the Bottom Roll within a window ")
(setq "OSMODE" 000)
(setq a (ssget "w" (setq crnpoint (getpoint))(getcorner crnpoint)))
(setq "OSMODE" os)
(command "REDRAW")
(command "CHANGE" a "PROP" "LAYER" "OUETC" "")
(command "LAYER" "SET" "OUETC" "")
(command "LAYER" "OFF" "" "")
(command "LAYER" "ON" "OUETC" "")
(command "PEDIT" ptn "" "J" a "")
(command "EXPLODE" ptn "")
(setq n 0)
(setq m 0)
(while
    (setq tbdata (tblnext "LAYER" frst))
    (setq m (1 + n))
    (setq n m)
    (setq frst nil)
)
(setq frst t
    bpt (getvar "INSBASE")
)
(prompt "\nInitializing the Database......Done")
(prompt "nProcessing the entity......Please do not interrupt")
(setq count 0)
(repeat n
   (setq tbdata (tblnext "LAYER" frst))
   (setq aa (cadr tbdata))
   (setq b (cdr aa))
   (setq lchk (/= b "OUETC"))
   (setq ents (ssget "X" (list (cons 8 b))))
   (if ents
       (if lchk
           (command "ERASE" ents "")
       )
   )
   (setq ents nil)
   (setq frst nil)
)
(setq b (sslength a))
(setq x 1)
(setq more 0)
(princ "nProcessing the data........")
(setq fn1 (open "botp.datH" w))
(setq ent (entnext))
(setq en (entget ent))
(redraw ent 3)
(setq vtn (cdr (assoc 0 en)))
(setq vtx (cdr (assoc 10 en)))
(setq vty (cdr (assoc 11 en)))
(setq vtr (cdr (assoc 40 en)))
(setq vtsa (cdr (assoc 50 en)))
(setq vtea (cdr (assoc 51 en)))
(if vtr
   (print vtr fn1)
   (print 0.0 fn1)
)
(if vtx fn1)
(if vtr fn1)
(if vtr fn1)
(if vtr fn1)
(if vty fn1)
)
(if (= b 1)
    (setq more nil)
)
(while more
    (setq x (+ x 1))
    (if (= x b)
        (setq more nil)
    )
    (setq ent (entnext ent))
    (setq en (entget ent))
    ;
    (command "DELAY" 100)
    (redraw ent 3)
    (setq vtn (cdr (assoc 0 en)))
    (setq vtx (cdr (assoc 10 en)))
    (setq vtr (cdr (assoc 40 en)))
    (setq vty (cdr (assoc 11 en)))
    (setq vtsa (cdr (assoc 50 en)))
    (setq vtea (cdr (assoc 51 en)))
    ;
    (print vtn fn1)
    (if vtr
        (print vtx fn1)
        (if vtr
            (print vtsa fn1)
            (if vtr
                (print vtea fn1)
                (if vty
                    (print vty fn1)
                    (print 0.0 fn1)
                )
            )
        )
    )
)
(close fn1)
(command "REDRAW")
(command "UNDO" "END")
(prompt "\nPlease wait........")
(command "UNDO" "BACK""
; (COMMAND "SHELL" "ABAQUS")
(graphscr)
(princ)
;function strip parentheses off coordinate points from topp.dat file.

(setq fpl (open "topp.dat" "r"))
(setq fp2 (open "topp.dat" "w"))

(while (setq line (read-line fpl))
  (setq line (read line))
  (if (not (atom line)) (progn
    (while (setq x (car line))
      (setq line (cdr line))
      (princ x fp2)
      (princ " " fp2)
    ))) ;end while
  (princ \n fp2)
); END PROGN, END IF
;else
  (if (/= LINE nil) (progn
    (princ line fp2)
    (princ \n fp2)
  )); END PROGN; end if
);end while
(close fp1)
(close fp2)

;function strip parentheses off coordinate points from botp.dat file.

(setq fpl (open "botp.dat" "r"))
(setq fp2 (open "botp.dat" "w"))

(while (setq line (read-line fpl))
  (setq line (read line))
  (if (not (atom line)) (progn
    (while (setq x (car line))
      (setq line (cdr line))
      (princ x fp2)
      (princ " " fp2)
    ))) ;end while
  (princ \n fp2)
); END PROGN, END IF
;else
  (if (/= LINE nil) (progn
    (princ line fp2)
    (princ \n fp2)
  )); END PROGN; end if
);end while
(close fp1)
(close fp2)
(princ line fp2)
(princ "\n" fp2)
)); END PROGN; end if
); end while
(close fp1)
(close fp2)
); end function cor
Appendix A2: FORTRAN Programs

C*******************************************************
PROGRAM QS_ABQ
C
C This program creates an ABAQUS input file for three-dimensional
C one quarter of symmetry rolling problems.
C
IMPLICIT INTEGER (H,I,J,K,L,M,N)
INTEGER IDI,C1(5),C3(9),IAUX,TR,PD
REAL TOP(100,5),BOT(100,5)
REAL K,N,F,EPSLON
REAL C(7),C2(4)
CHARACTER*1 ANS,D1(3)
CHARACTER*2 DIM
CHARACTER*12 MAT
CHARACTER*12 NAME
CHARACTER*30 A(7),A1(9,2),A2(4),A3(9)
CHARACTER*48 HEADING
PARAMETER(PI=3.14159265359)
C
C *** Definition of variables ***
C
C Dimensions should be in consistent units
C
C TRD = Maximum Top Roll Diameter
C RS = Roll Speed (RPM)
C SS = initial Stock Size
C RG = Roll Gap
C MAT= Material name
C E = Modulus of Elasticity
C V = Poisson's Ratio
C BL = Billet Length
C F = Coefficient of friction
C PR = Percentage of reduction at intersecting diameter
C K = Flow stress coefficient
C N = Strain hardening coefficient
C NX = Number of layers in the X direction
C NY = Number of layers in the Y direction
C NZ = Number of layers in the Z direction
C TR = Top Roll representative node number
C PD = Push die representative node number
C BW = Billet width
C
CALL the subroutine that gets the coordinates of the rolls from the AutoCad drawings

CALL COD(TOP,BOT,NBOT,NTOP,BRD,TRD)

TRD=TRD*2
BRD=BRD*2

WRITE(6,900)
900  FORMAT(/,' Enter name of the ABAQUS input file (NAME.INP) --> ','$)
READ(6,910)NAME

WRITE(6,1000)
1000 FORMAT(/,' Enter the Main Title of this rolling problem --> ','$)
READ(5,1010)HEADING

WRITE(6,1020)
1020 FORMAT(/,15X,'*** ROLL PARAMETERS ***',/)

A(1) = 'A. Intersecting Roll Radius'
A(2) = 'B. Roll speed (RPM)'
A(3) = 'C. Initial Stock Size'
A(4) = 'D. Billet Width'
A(5) = 'E. Billet Length'
A(6) = 'F. Friction factor'
A(7) = 'G. Material File Name'

DIM = 'm'
WRITE(6,1021)
1021 FORMAT(/,' Dimensions are in meters (1) or inches (2) ?'
& 1, <1> -- > ','$)
READ(5,1007,ERR=1022)IDI

1007 FORMAT(I1)
IF(IDI.EQ.2)DIM = 'in'

CONTINUE

WRITE(6,1020)

DO 1055 I=1,6
WRITE(6,1037)A(I)
1037 FORMAT(/,/,A33)
1057 WRITE(6,1056)
1056 FORMAT(/,' Enter value -->'],$)
READ(5,*,ERR=1057)C(I)
1055 CONTINUE
C
MAT='AISI1045.MAT'
1077 WRITE(6,1075)A(7),MAT
1075 FORMAT(/,/,A13,' <',A12,' > -->'],$)
READ(5,1076,ERR=1077)MAT
1076 FORMAT(A12)
IF(MAT.EQ.' ')MAT='AISI1045.MAT'
1061 WRITE(6,1020)
C
DO 1058 I=1,6
WRITE(6,1060)A(I),C(I)
1060 FORMAT(/,5X,A33,'=',I1P,E12.5)
1058 CONTINUE
C
WRITE(6,1082)A(7),MAT
1082 FORMAT(/,5X,A33,1X,'=',A12)
C
1067 WRITE(6,1043)
1043 FORMAT(/,' Do you need to correct any value ? (Y/N) <N>--->$)
READ(5,2172,ERR=1067)ANS
2172 FORMAT(A1)
IF(ANS.EQ.'Y'.OR.ANS.EQ.'y')THEN
DO 28 I=1,6
WRITE(6,1037)A(I)
1037 WRITE(6,1064)C(I)
1065 WRITE(6,1064)C(I)
1064 FORMAT(/,' Current value =',1P,E12.5,' Change ? (Y/N) <N>--->$)
READ(5,2172,ERR=1065)ANS
IF(ANS.EQ.'Y'.OR.ANS.EQ.'y')THEN
WRITE(6,1056)
READ(5,*,ERR=28)C(I)
ENDIF
28 CONTINUE
GOTO 1061
1088 WRITE(6,1087)A(7),MAT
1087 FORMAT(/,2X,A15,' = ',A12,' Change ? (Y/N) <N>--->$)
READ(5,2172,ERR=1088)ANS
IF(ANS.EQ.'Y'.OR.ANS.EQ.'y')THEN
WRITE(6,1075)A(7),MAT

READ(5,1076,ERR=1088)MAT
IF(MAT.EQ.' ')MAT='AISI1045.MAT'
ENDIF
ENDIF

C
C Get the material properties from the file
C
OPEN(UNIT=4,FILE=MAT,STATUS='UNKNOWN')
READ(4,1076)MAT
READ(4,*)E
READ(4,*)V
READ(4,*)K
READ(4,*)N
CLOSE(UNIT=4)

C
C Set default values for simulation parameters
C
WRITE(6,1070)
1070 FORMAT(/,/,/,lOX,' *** SIMULATION PARAMETERS ***')
C
A1(1,1)= 'Elements in the X direction'
C1(1)=40
A1(2,1)= 'Elements in the Y direction'
C1(2)=5
A1(3,1)= 'Elements in the Z direction'
C1(3)=5
A1(4,1)= 'Top roll reference node'
C1(4)=99999
A1(5,1)= 'Push die reference node'
C1(5)=88888
A1(6,1)= 'Mesh plots'
D1(1)= 'N'
A1(6,2)= '(Y/N)'
A1(7,1)= 'File format ASCII or Binary'
D1(2)= 'A'
A1(7,2)= '(A/B)'
A1(8,1)= 'Plot format ASCII or Binary'
D1(3)= 'A'
A1(8,2)= '(A/B)'

C
DO 1071 I=1,8
C
IF(I.LE.5)THEN
IAUX=0
WRITE(6,1072)A1(l,1),C1(l)
1072 FORMAT(/,' Enter ',A33,'<','|','> --> ','$)
READ(5,1073,ERR=1074)IAUX
IF(IAUX.NE.0)C1(l)=IAUX
1073 FORMAT(I5)
C
ELSE
ANS=''
1079 WRITE(6,1078)A1(l,1),A1(l,2),D1(l-5)
1078 FORMAT(/,' Enter ',A33,' ','A13','<','A1','> -->'$)
READ(5,2172,ERR=1079)ANS
IF(ANS.NE.' ')D1(l-5)=ANS
ENDIF
C
1071 CONTINUE
C
1093 WRITE(6,1070)
DO 1080 I=1,8
IF(I.LE.5)THEN
WRITE(6,1081)A1(l,1),C1(l)
1081 FORMAT(/,5X,A33,8X,I5)
ELSE
WRITE(6,1083)A1(l,1),D1(l-5)
1083 FORMAT(/,5X,A33,11X,A1)
ENDIF
1080 CONTINUE
C
1084 WRITE(6,1043)
READ(5,2172,ERR=1084)ANS
IF(ANS.EQ.'Y'.OR.ANS.EQ.'y')THEN
DO 1095 I=1,8
C
IF(I.LE.5)THEN
IAUX=0
1086 WRITE(6,1094)A1(l,1),C1(l)
1094 FORMAT(/,2X,A33,'= ','|',' Change ? (Y/N) <N> -->'$)
READ(5,2172,ERR=1086)ANS
IF(ANS.EQ.'Y'.OR.ANS.EQ.'y')THEN
WRITE(6,1072)A1(l,1),C1(l)
1085 READ(5,1073,ERR=1085)IAUX
IF(IAUX.NE.0)C1(l)=IAUX
ENDIF
C
ELSE

WRITE(6,1091)A1(1,1),D1(1-5)

FORMAT(/,2X,A11,'=',A1,' Change ? (Y/N) <N> ---->',$)
READ(5,2172,ERR=1090)ANS
IF(ANS.EQ.'Y'.OR.ANS.EQ.'y')THEN
   ANS=''
ENDIF

WRITE(6,1078)A1(1,1),A1(1,2),D1(1-5)
READ(5,2172,ERR=1092)ANS
IF(ANS.NE.' ')D1(I-5)=ANS
ENDIF

CONTINUE

GOTO 1093

ENDIF

C

Set the PTOL tolerance. First calculate an approximate contact pressure.

TID=C(1)
RS=C(2)*PI/30.0
SS=C(3)
BW=C(4)
BL=C(5)
F=C(6)
RD=2*TID
RG=(TOP(1,2)-TID)*2
XXL=SQRT(0.5*TRD*ABS(SS-RG))
XH=0.5*(SS+RG)
SIG0=K*((ALOG(SS/RG))**N)
YIELD=K*((0.02)**N)
PA=XH/(F*XXL)*(EXP(F*XXL/XH)-1)*SIG0
FAX=PA*XXL*BW
PTOL=FAX/1500

WRITE(6,4005)

FORMAT(/,/,/13X,'*** MODEL HISTORY PARAMETERS ***',/,,/)
\[ XT = XF \]
\[ T = \frac{2 \times XT}{(RS \times RD)} \]
\[ RAD = RS \times T \]

C

A2(1) = 'Length percentage to be rolled'
C2(1) = XF/BL*100
A2(2) = 'Initial Time increment'
C2(2) = T*1.E-5
A2(3) = 'Minimum Time increment'
C2(3) = T*1.E-15
A2(4) = 'Residual Tolerance PTOL'
C2(4) = PTOL

C

MAX = 3000
C

IAUX = 0
4002 WRITE(6,4001)MAX
4001 FORMAT(/,' Enter Maximum Number of Increments  <', & I5,' > --->',$)
READ(5,4030,ERR=4002)IAUX
4030 FORMAT(I5)
IF(IAUX.NE.0)MAX=IAUX
C

DO 4010 I=1,4
   AUX = 0.0
4011 WRITE(6,4015)A2(I),C2(I)
4015 FORMAT(/,' Enter ',A23,' <',1P,E12.3,' > --->',$)
READ(5,4029,ERR=4011)AUX
IF(AUX.NE.0.0)C2(I)=AUX
4029 FORMAT(E12.3)
4010 CONTINUE
C

4016 WRITE(6,4005)
   WRITE(6,4017)MAX
4017 FORMAT(/,3X,'Maximum Number of Increments = ',I5)
   DO 4020 I=1,4
      WRITE(6,4018)A2(I),C2(I)
4018 FORMAT(/,3X,A23,' = ',1P,E12.3)
4020 CONTINUE
C
4019 WRITE(6,1043)
C
   READ(5,2172,ERR=4019)ANS
   IF(ANS.EQ.'Y'.OR.ANS.EQ.'y')THEN
DO 4025 I = 1, 4
        WRITE(6, 4027) A2(I), C2(I)
        READ(5, 2172, ERR=4027) A2, C2
        IF (AUX.NE.0.0) C2(I) = AUX
        ENDIF
        CONTINUE
C
      GOTO 4016
C
      ENDF
C
      C2(1) = C2(1) * BL/100
      XL = C2(1)
      Z = SQRT((0.5*RD)**2 - (0.5*RD - 0.5*(SS-RG))**2)
      XT = XL
      T = (2*XT)/(RS*RD)
      RAD = RS*T
      TIT = C2(2)
      TMI = C2(3)
C
      WRITE(6, 4031)
      FORMAT(//, //, /3X, *** POST-PROCESSING PARAMETERS ***', //, //)
C
      WRITE(6, 4032)
      FORMAT(//, ' This set of Parameters control the Printing',
            &/, ' Frequency of the simulation results ', //, //)
      A3(1) = 'Convergence print'
      C3(1) = 300
A3(2)='RESTART FILE'
C3(2)=40
A3(3)='Mises/Eq. Pl. Strain FILE'
C3(3)=40
A3(4)='Outside Coord.(AREA) PRINT'
C3(4)=40
A3(5)='Contact Stresses PRINT'
C3(5)=40
A3(6)='PUSH print'
C3(6)=10
A3(7)='ROLL print'
C3(7)=10
A3(8)='TOP print'
C3(8)=40
A3(9)='PLOTS'
C3(9)=40
C
DO 4033 I=1,9
C
IAUX=0
4037 WRITE(6,4035)A3(I),C3(I)
4035 FORMAT(/,' Enter Frequency of ','A24,' <','I3,' > --->',$)
READ(5,4036,ERR=4037)IAUX
4036 FORMAT(I3)
IF(IAUX.NE.0)C3(I)=IAUX
C
4033 CONTINUE
C
4038 WRITE(6,4031)
DO 4039 I=1,9
WRITE(6,4040)A3(I),C3(I)
4040 FORMAT(/,3X,'Frequency of ','A24,' = ','I3,)
4039 CONTINUE
C
4041 WRITE(6,1043)
READ(5,2172,ERR=4041)ANS
IF(ANS.EQ. 'Y'.OR.ANS.EQ. 'y')THEN
DO 4044 I=1,9
IAUX=0
4046 WRITE(6,4045)A3(I),C3(I)
4045 FORMAT(/,' Frequency of ','A24,' = ','I3, & ' Change ? (Y/N) <N> --->',$)
READ(5,2172,ERR=4046)ANS
IF(ANS.EQ. 'Y'.OR.ANS.EQ. 'y')THEN
4047 WRITE(6,4035)A3(l),C3(l)
READ(5,4036,ERR=4047)IAUX
IF(IAUX.NE.0)C3(l)=IAUX
ENDIF
4044 CONTINUE
GOTO 4038
ENDIF
C
C Open the input file
C
OPEN(UNIT=8,FILE=NAME,STATUS='UNKNOWN')
C
WRITE(8,2020)
2020 FORMAT('*HEADING,UNSYMM')
C
WRITE(8,1009)NAME,HEADING
1009 FORMAT(A12,'.',A48)
C
WRITE(8,2025)0.5*TRD,DIM
2025 FORMAT('Maximum Roll Radius = ',1P,E12.5,1X,A2)
C
WRITE(8,2040)RG,DIM
2040 FORMAT('Roll Gap at Intersection = ',1P,E12.5,1X,A2)
C
WRITE(8,2041)TID,DIM
2041 FORMAT('Intersecting Roll Radius = ',1P,E12.5,1X,A2)
C
WRITE(8,2030)RS*30/PI
2030 FORMAT('Roll Speed = ',1P,E12.5,' RPM')
C
WRITE(8,2035)SS,DIM
2035 FORMAT('Initial Billet Thickness = ',1P,E12.5,1X,A2)
C
WRITE(8,2036)BW,DIM
2036 FORMAT('Initial Billet Width = ',1P,E12.5,1X,A2)
C
WRITE(8,2045)BL,DIM
2045 FORMAT('Initial Billet Length = ',1P,E12.5,1X,A2)
C
WRITE(8,2050)F
2050 FORMAT('Friction = ',F10.3)
C
WRITE(8,2056)MAT
2056 FORMAT('Material File Name = ',A12)
C
WRITE(8,2060)E
2060 FORMAT('Young Modulus = ',1P,E12.5)
C
WRITE(8,2061)V
2061 FORMAT('Poisson Ratio = ',F5.3)
C
WRITE(8,2062)K
2062 FORMAT('Strength coefficient = ',1P,E12.5)
C
WRITE(8,2063)N
2063 FORMAT('Strain Hardening coef. = ',F5.3)
C
EPSLON=BL/8000
C
WRITE(8,3295)C3(2)
3295 FORMAT('*RESTART,WRITE,FREQUENCY=',I3)
C
WRITE(8,3000)
3000 FORMAT('** Start Model Definition **')
C
TR=C1(4)
WRITE(8,3005)
3005 FORMAT('*NODE,NSET=ROLL')
WRITE(8,2065)TR,-1*EPSLON,TOP(1,2),TOP(1,3)
2065 FORMAT(15,',',1P,E12.5,',',E12.5,',',E12.5)
C
XB=SQRT((TID)**2-(0.5*SS-TOP(1,2))**2)
YB=0.5*SS
ZB=0.0
YBZ=YB
XZB=XB
ZBZ=-0.5*BW
C
XC=XB+BL
YC=0.5*SS
ZC=0.0
XCZ=XC
YCZ=YC
ZCZ=-0.5*BW
C
XD=XB+BL
YD=0.0
ZD=0.0
XDZ=XD
YDZ=YD
ZDZ=-0.5*BW

C
XE=XB
YE=0.0
ZE=0.0
XEZ=XE
YEZ=YE
ZEZ=-0.5*BW

C
PD=C1(5)
WRITE(8,2066)
2066 FORMAT('*NODE,NSET=PUSH')
WRITE(8,2065)PD, XC + EPSLON, 1.1*YC, 0.0

C
WRITE(8,2067)
2067 FORMAT('* Define nodes in the billet **')
WRITE(8,2068)
2068 FORMAT('*NODE')
C
NX=C1(1)
NY=C1(2)
NZ=C1(3)

C
NE=1
NEZ=NE+NZ*1000

C
ND=NE+NX
NDZ=ND+NZ*1000

C
NB=NY*100+NE
NBZ=NB+NZ*1000

C
NC=NY*100+ND
NCZ=NC+NZ*1000

C
WRITE(8,2065)NE, XE, YE, ZE

C
WRITE(8,2065)ND, XD, YD, ZD

C
WRITE(8,2065)NB, XB, YB, ZB

C
WRITE(8,2065)NC, XC, YC, ZC
WRITE(8,2065) NEZ,XEZ,YEZ,ZEZ
WRITE(8,2065) NDZ,XDZ,YDZ,ZDZ
WRITE(8,2065) NBZ, XBZ, YBZ, ZBZ
WRITE(8,2065) NCZ, XCZ, YCZ, ZCZ
WRITE(8,3015)
3015 FORMAT('*NGEN,NSET=BLLINE')
WRITE(8,2070) NE, ND
WRITE(8,3025)
3025 FORMAT('*NGEN,NSET=TLLINE')
WRITE(8,2070) NB, NC
WRITE(8,3027)
3027 FORMAT('*NGEN,NSET=FRONTL')
WRITE(8,2080) NE, NB, 100
WRITE(8,3029)
3029 FORMAT('*NGEN,NSET=BACKL')
WRITE(8,2080) ND, NC, 100
WRITE(8,3016)
3016 FORMAT('*NGEN,NSET=BRLINE')
WRITE(8,2070) NEZ, NDZ
WRITE(8,3026)
3026 FORMAT('*NGEN,NSET=TRLINE')
WRITE(8,2070) NBZ, NCZ
WRITE(8,3028)
3028 FORMAT('*NGEN,NSET=FRONTR')
WRITE(8,2080) NEZ, NBZ, 100
WRITE(8,3031)
3031 FORMAT('*NGEN,NSET=BACKR')
WRITE(8,2080) NDZ, NCZ, 100
WRITE(8,3040)
3040  FORMAT(*NFILL,NSET=STOCKL*)
       WRITE(8,2075)'BLLINE,TLLINE,\',NY,100
2075  FORMAT(A14,I2,\',\',I3)
C
       WRITE(8,3041)
3041  FORMAT(*NFILL,NSET=STOCKR*)
       WRITE(8,2075)'BRLINE,TRLINE,\',NY,100

       WRITE(8,3084)
3084  FORMAT(*NFILL,NSET=STOCK*)
       WRITE(8,3085)NZ,1000
3085  FORMAT('STOCKL,STOCKR,\',I2,\',\',I4)
C
       WRITE(8,3082)
3082  FORMAT(*NFILL,NSET=BOTTOM*)
       WRITE(8,3083)NZ,1000
3083  FORMAT('BLLINE,BRLINE,\',I2,\',\',I4)
C
       WRITE(8,3055)
3055  FORMAT(*NFILL,NSET=TOP*)
       WRITE(8,3056)NZ,1000
3056  FORMAT('TLLINE,TRLINE,\',I2,\',\',I4)
C
       WRITE(8,3093)
3093  FORMAT(*NFILL,NSET=FRONT*)
       WRITE(8,3094)NZ,1000
3094  FORMAT('FRONTL,FRONTR,\',I2,\',\',I4)
C
       WRITE(8,3096)
3096  FORMAT(*NFILL,NSET=BACK*)
       WRITE(8,3097)NZ,1000
3097  FORMAT('BACKL,BACKR,\',I2,\',\',I4)
C
       WRITE(8,3440)
3440  FORMAT(*NSET,NSET=AREA*)
       WRITE(8,3445)
3445  FORMAT('BOTTOM,STOCKL,STOCKR,TOP,FRONT,BACK*)
       WRITE(8,3086)
3086  FORMAT('** Generate Elements ***)
C
       WRITE(8,3090)
3090  FORMAT(*ELEMENT,TYPE=C3D8R,ELSET=BILLET*)
       WRITE(8,3095)
3095  FORMAT('1,1001,1002,1102,1101,1,2,102,101\')
C
WRITE(8,3100)
3100 FORMAT('**ELGEN,ELSET=BILLET')
WRITE(8,2085)NE,ND-1,1,1, NY,100,100,NZ,1000,1000
2085 FORMAT(I1,,I3,,I1,,I1,4,,I3,,I4,,I4)
C
WRITE(8,3105)
3105 FORMAT('**ELEMENT,TYPE=IRS13')
WRITE(8,2090)901,NB,TR
WRITE(8,2090)20001,NEZ,TR
WRITE(8,2090)801,NC,PD
C
2090 FORMAT(2(I5,,),I5)
C
WRITE(8,3115)
3115 FORMAT('**ELGEN,ELSET=TRLL')
WRITE(8,2095)901,ND-1,1,1,100,100,NZ+1,1000,1000
2095 FORMAT(I5,,I3,3,,I1,3,,I3,,I4,,I4)
C
WRITE(8,5115)
5115 FORMAT('**ELGEN,ELSET=SRLL')
WRITE(8,2095)20001,ND-1,1,1, NY,100,100,1,1000,1000
C
WRITE(8,5120)
5120 FORMAT('**ELSET,ELSET=TROLL')
WRITE(8,5123)
5123 FORMAT('TRLL,SRLL')
C
WRITE(8,3110)
3110 FORMAT('**ELGEN,ELSET=FOLD')
WRITE(8,2096)801,1,1,1, NY+1,-100,1,NZ+1,1000,1000
2096 FORMAT(I3,3,,I1,2,,I4,,I1,,I3,,I4,,I4)
C
WRITE(8,3120)
3120 FORMAT('** Define Rigid Surfaces **')
WRITE(8,3125)
3125 FORMAT('**RIGID SURFACE,ELSET=TROLL,, + 'TYPE=AXISYMMETRIC')
WRITE(8,3415)-1*EPSLON,TOP(1,2),TOP(1,3),
+    -1*EPSLON,TOP(2,2),TOP(2,3)
3415 FORMAT(1P,E12.5,,1P,E12.5)
WRITE(8,2100)TOP(3,2),TOP(3,3)
DO 6005 I=4,NTOP+3
IF(TOP(I,1).GT.0.0)THEN
WRITE(8,3401)TOP(I,2),TOP(I,3),TOP(I,4),TOP(I,5)
ELSE
WRITE(8,3400)TOP(I,2),TOP(I,3)
ENDIF
6005 CONTINUE
C
3400 FORMAT('LINE,',1P,E12.5,','E12.5)
3401 FORMAT('CIRCL,',1P,E12.5,','E12.5,'','E12.5,','E12.5,'','E12.5)
2100 FORMAT('START,',1P,E12.5,','E12.5)
C
WRITE(8,3130)
3130 FORMAT('**RIGID SURFACE,ELSET=FOLD,TYPE=CYLINDER')
WRITE(8,3415)EPSLON+XD,YD,0.1*BW,EPSLON+XC,YC,0.1*BW
WRITE(8,3405)EPSLON+XDZ,YDZ,-0.6*BW
3405 FORMAT(1P2(E12.5,','),E12.5)
WRITE(8,2100)-1.5E-3,O.0
WRITE(8,3400)1.4*YC,0.0
C
WRITE(8,3135)
3135 FORMAT('** Define frictional conditions **')
WRITE(8,3140)
3140 FORMAT('**INTERFACE,ELSET=FOLD')
WRITE(8,3450)0.25*BW*SS/((NY+1)*(NZ+1))
3450 FORMAT(1P,E12.5,','0.0,1.0,0.0')
WRITE(8,3145)
3145 FORMAT('**FRICTION')
WRITE(8,3150)
3150 FORMAT('1.E15,1.E15')
C
WRITE(8,3155)
3155 FORMAT('**INTERFACE,ELSET=TRLL')
WRITE(8,3455)0.5*BW*BL/((NX+1)*(NZ+1))
3455 FORMAT(1P,E12.5,','0.0,1.0,0.0')
WRITE(8,3145)
DIS=BL/(NX*2)
ST=PA/DIS
WRITE(8,2115)F,ST,K*((0.03)**N)
C
WRITE(8,5155)
5155 FORMAT('**INTERFACE,ELSET=SRLL')
WRITE(8,5455)0.5*SS*BL/((NX+1)*(NY))
5455 FORMAT(1P,E12.5,','0.0,0.0,-1.0')
WRITE(8,3145)
C
WRITE(8,2115)F,ST,K*((O.03)**N)
2115 FORMAT(F5.3,'
'1P,E12.5,'
',E12.5)
C
WRITE(8,3160)
3160 FORMAT('** Define Material Properties **')
WRITE(8,2120)MAT
2120 FORMAT('*SOLID SECTION,ELSET=BILLET,MATERIAL=',A4)
WRITE(8,2125)MAT
2125 FORMAT('*MATERIAL,NAME=',A4)
C
WRITE(8,3165)
3165 FORMAT('**ELASTIC')
WRITE(8,2130)E,V
2130 FORMAT(1P,E12.5,'
',E8.2)
C
WRITE(8,3170)
3170 FORMAT('**PLASTIC,HARD=ISO')
WRITE(8,2135)K*((.02)**N),0.0
DO 30 X=0.1,5.0,.1
SIG=K*((X)**N)
WRITE(8,2135)SIG,X
30 CONTINUE
2135 FORMAT(1P,E12.5,'
',E12.3)
C
IF(D1(1).EQ.'N'.OR.D1(1).EQ.'n')THEN
GOTO 2150
ELSE
IF(D1(3).EQ.'A'.OR.D1(3).EQ.'a')THEN
WRITE(8,3425)
3425 FORMAT('**PLOT,OUTPUT=ASCII')
ELSE
WRITE(8,3195)
3195 FORMAT('**PLOT')
ENDIF
WRITE(8,3430)
3430 FORMAT('**VIEWPOINT')
WRITE(8,3435)1.0,1.0,1.0,0.0,1.0,0.0
3435 FORMAT(F4.1,5(',',F4.1))
WRITE(8,3200)
3200 FORMAT('**DRAW,HIDE')
C
WRITE(8,3430)
WRITE(8,3435)-1.0,1.0,0.0,0.0,1.0,0.0
WRITE(8,3200)
WRITE(8,3430)
WRITE(8,3435) 0.0, 0.0, 1.0, 0.0, 1.0, 0.0
WRITE(8,3200)

C
ENDIF
C
2150 CONTINUE
WRITE(8,3210)
3210 FORMAT('*** Start History Definition ***)
C
WRITE(8,2175) MAX
2175 FORMAT('*STEP,INC=',I5,',CYCLE=15,SUBMAX,MONOTONIC,',
&'NLGEOM,AMP=RAMP')
C
WRITE(8,3211)
3211 FORMAT('Push the billet slowly. Rolls are turning')
C
WRITE(8,3215) PTOL
3215 FORMAT('*STATIC,PTOL=','P,E12.5')
C
WRITE(8,3220) TIT, T, TMI
3220 FORMAT(1P, 2(E12.5, ','), E12.5)
C
IF(D1(2).EQ.'A'.OR.D1(2).EQ.'a')THEN
WRITE(8,3225)
3225 FORMAT('*FILE FORMAT,ASCII')
ENDIF
C
WRITE(8,3230)
3230 FORMAT('*BOUNDARY')
WRITE(8,3235)
3235 FORMAT('BOTTOM,2')
C
WRITE(8,3194)
3194 FORMAT('STOCKL,3')
C
WRITE(8,3240)
3240 FORMAT('ROLL,1,5')
WRITE(8,3245)-0.25*XT
3245 FORMAT('PUSH,1,1,','P,E12.4')
WRITE(8,3251)
3251 FORMAT('PUSH,2,6')
WRITE(8,3260)-1*RAD
3260  FORMAT('ROLL,6,6, ,1P,E12.4)
C
     WRITE(8,3270)C3(1)
3270  FORMAT('*PRINT,CONTACT=NO,RESIDUAL=NO,FREQUENCY=',I3)
C
     WRITE(8,3299)C3(3)
3299  FORMAT('*EL FILE,ELSET=BILLET,FREQUENCY=',I3)
     WRITE(8,3300)
3300  FORMAT('SINV,PE')
C
     WRITE(8,3580)C3(5)
3580  FORMAT('*EL FILE,ELSET=TROLL,FREQUENCY=',I3)
     WRITE(8,3585)
3585  FORMAT('S')
C
     WRITE(8,3325)C3(4)
3325  FORMAT('*NODE FILE,NSET=AREA,FREQUENCY=',I3)
     WRITE(8,3326)
3326  FORMAT('COORD')
C
     WRITE(8,3570)C3(3)
3570  FORMAT('*NODE FILE,NSET=STOCK,FREQUENCY=',I3)
     WRITE(8,3575)
3575  FORMAT('U')
C
     WRITE(8,3500)1
3500  FORMAT('*NODE FILE,NSET=PUSH,FREQUENCY=',I3)
     WRITE(8,3346)
C
     WRITE(8,3505)1
3505  FORMAT('*NODE FILE,NSET=ROLL,FREQUENCY=',I3)
     WRITE(8,3346)
C
     WRITE(8,3327)C3(4)
3327  FORMAT('*NODE PRINT,NSET=AREA,FREQUENCY=',I3)
     WRITE(8,3328)
3328  FORMAT('COOR3,COOR2')
C
     WRITE(8,3335)C3(6)
3335  FORMAT('*NODE PRINT,NSET=PUSH,FREQUENCY=',I3,';SUMMARY=NO')
     WRITE(8,3336)
3336  FORMAT('COOR1,U1,RF1')
C
     WRITE(8,3345)C3(7)
FORMAT('*NODE PRINT,NSET=ROLL,FREQUENCY=','I3','SUMMARY=NO')
WRITE(8,3346)
3346 FORMAT('RF')
C
WRITE(8,4580)C3(5)
4580 FORMAT('*EL PRINT,ELSET=TROLL,FREQUENCY=','I3')
WRITE(8,4585)
4585 FORMAT('S11,S12,S13')
C
IF(D1(1).EQ.'N'.OR.D1(1).EQ.'n')THEN
C
GOTO 4004
C
ELSE
C
IF(D1(3).EQ.'A'.OR.D1(3).EQ.'a')THEN
WRITE(8,3366)C3(9)
3366 FORMAT('*PLOT,OUTPUT=ASCII,FREQUENCY=','I3)
ELSE
WRITE(8,3367)C3(9)
3367 FORMAT('*PLOT,FREQUENCY=','I3)
ENDIF
C
WRITE(8,3370)
WRITE(8,3375)1.0,1.0,1.0,0.0,1.0,0.0
WRITE(8,3370)
3370 FORMAT('*DETAIL,ELSET=BILLE')
WRITE(8,3375)
3375 FORMAT('*CONTOUR')
WRITE(8,3376)
3376 FORMAT('PEEQ')
WRITE(8,3375)
WRITE(8,3380)
3380 FORMAT('MISES')
C
ENDIF
C
4004 CONTINUE
C
WRITE(8,3385)
3385 FORMAT('*END STEP')
C
WRITE(6,3390)NAME
3390 FORMAT(/,/,'*** ABAQUS IMPUT FILE = ','A12,' CREATED ***')
CLOSE (UNIT=8)
C
END
C******************************************************************************
C
SUBROUTINE COD (TOP, BOT, NBOT, NTOP, BRD, TRD)
C
This SUBROUTINE uses AutoCad coordinates to define the
shape of the rolls as rigid surfaces in ABAQUS
C
The format of array TOP is:
C TOP(1,1)=global x coord. of a in top roll
C TOP(1,2)=global y coord. of a in top roll
C TOP(1,3)=global z coord. of a in top roll
C TOP(2,1)=global x coord. of b in top roll
C TOP(2,2)=global y coord. of b in top roll
C TOP(2,3)=global z coord. of b in top roll
C TOP(3,1)=0.0
C TOP(3,2)=local x coord. of START point
C TOP(3,3)=local y coord. of START point
C
The next entries are:
C TOP(i,1)= 0 for a line segment and
C TOP(i,2)=local x coord. of end point
C TOP(i,3)=local y coord. of end point
C or
C TOP(i,1)= 1 for a circular segment and
C TOP(i,2)=local x coord. of end point
C TOP(i,3)=local y coord. of end point
C TOP(i,4)=local x coord. of center point
C TOP(i,5)=local y coord. of center point
C
array BOT follows a similar format
C A maximum number of 100 segments has been set (S MAX)
C
NTOP --> number of segments in the top roll
C NBOT --> number of segments in the bottom roll
C CLOCKTOP--> greater than zero for CLOCKWISE
C lower than zero for ANTICLOCKWISE
C CLOCKBOT--> greater than zero for CLOCKWISE
C lower than zero for ANTICLOCKWISE
C
IMPLICIT INTEGER (H,I,J,K,L,M,N)
PARAMETER (PI=3.14159265359)
REAL TOP(100,5),BOT(100,5),TOPX(100,5),BOTX(100,5) 
REAL TRD,BRD,T1,T2,T3,X,Y,Z,X1,Y1,Z1,R 
C 
C The TOP roll should be entered CLOCKWISE 
C 
CLOCKTOP=1.0 
C 
C The BOTTOM roll should be entered ANTICLOCKWISE 
C 
CLOCKBOT=-1.0 
C 
File TOP.DAT always has the TOP roll coordinates 
C 
OPEN(UNIT=2,FILE='TOP.DAT',STATUS='OLD') 
C 
READ(2,*)R 
C 
IF(R.GT.0.0)THEN 
WRITE(6,10) 
10 FORMAT(/,'** ERROR: Roll profiles cannot start', 
&'or end with an arc segment **') 
STOP 
ENDIF 
C 
This set of LOOPS are to read the coordinates of points 
a and b of the TOP and BOTTOM rolls. Points a and b 
are defined according to the rigid surface specifications 
of the ABAQUS user’s manual version 4.8. 
C 
NTOP=1 
READ(2,*)XTB,YTB,ZTB 
READ(2,*)X,Y,Z 
C 
DO 25 I=1,1000 
READ(2,*,END=30)R 
IF(R.GT.0.0)THEN 
READ(2,*)X,Y,Z 
NTOP=NTOP+1 
READ(2,*)SA 
READ(2,*)EA 
ELSE 
READ(2,*)X,Y,Z 
READ(2,*)XTA,YTA,ZTA 
NTOP=NTOP+1
ENDIF
25 CONTINUE
C
30 CONTINUE
C
REWIND (UNIT=2)
C
Check the direction in which the coordinates are given
C
Check if the direction of the top roll is antilockwise
IF(XTA.GT.XTB)THEN
  CLOCKTOP=-1.0
  T1=XTA
  T2=YTA
  T3=ZTA
  XTA=XTB
  YTA=YTB
  ZTA=ZTB
  XTB=T1
  YTB=T2
  ZTB=T3
ENDIF
C
File BOT.DAT always has the BOTTOM roll coordinates
C
OPEN(UNIT=3,FILE='BOT.DAT',STATUS='OLD')
C
READ(3,*)R
C
IF(R.GT.0.0)THEN
  WRITE(6,10)
  STOP
ENDIF
C
NBOT=1
READ(3,*)XBB,YBB,ZBB
READ(3,*)X,Y,Z
C
DO 35 I=1,1000
  READ(3,*,END=40)R
  IF(R.GT.0.0)THEN
    READ(3,*)X,Y,Z
    NBOT=NBOT+1
    READ(3,*)SA
  ENDIF
35 CONTINUE
READ(3,*) EA
ELSE
READ(3,*) X,Y,Z
READ(3,*) XBA,YBA,ZBA
NBOT=NBOT+1
ENDIF

CONTINUE

CONTINUE

REWIND (UNIT=3)

Check the direction in which the coordinates are given
The direction of the BOTTOM roll is clockwise
IF(XBA.GT.XBB) THEN
CLOCKBOT=1.0
T1=XBA
T2=YBA
T3=ZBA
XBA=XBB
YBA=YBB
ZBA=ZBB
XBB=T1
YBB=T2
ZBB=T3
ENDIF

Define ABAQUS GLOBAL coordinates for points a and b of the Top and Bottom rolls.
Top roll point a global coordinates
XA=0.0
YA=(YTA-YBA)/2
ZA=(XTA-XTB)/2

TOP(1,1)=XA
TOP(1,2)=YA
TOP(1,3)=ZA

Top roll point b global coordinates
XB=0.0
YB=(YTB-YBB)/2
ZB=(XTB-XTA)/2
TOP(2,1) = XB
TOP(2,2) = YB
TOP(2,3) = ZB

DO 45 I = 4, 1000

READ(2,*, END=50) R
IF(R.GT.0.0) THEN
  READ(2,*) X, Y, Z
  READ(2,*) SA
  READ(2,*) EA
  TOPX(I,1) = R
  TOPX(I,2) = X
  TOPX(I,3) = Y
  TOPX(I,4) = SA
  TOPX(I,5) = EA
ELSE
  READ(2,*) X1, Y1, Z1
  READ(2,*) X, Y, Z
  TOPX(I,1) = 0.0
  TOPX(I,2) = X1
  TOPX(I,3) = Y1
  TOPX(I,4) = X
  TOPX(I,5) = Y
ENDIF

45 CONTINUE

50 CONTINUE

IF(CLOCKTOP.LT.0.0) THEN
  DO 122 I = 4, NTOP + 3
    DO 123 J = 1, 5
      TOP(I,J) = TOPX(NTOP + 7 - I, J)
  123 CONTINUE
  122 CONTINUE

120 CONTINUE

DO 300 I = 4, NTOP + 3
  IF(TOP(I,1).LE.0.0) THEN
    X1 = TOP(I,2)
    Y1 = TOP(I,3)
    TOP(I,2) = TOP(I,4)
    TOP(I,3) = TOP(I,5)
TOP(I,4)=X1
TOP(I,5)=Y1
ENDIF
300 CONTINUE
ELSE
   DO 222  I=4,NTOP+3
   DO 223  J=1,5
          TOP(I,J)=TOPX(I,J)
   223 CONTINUE
222 CONTINUE
ENDIF

C
C Now we have to do something with the first points
TOP(3,1)=0.0
TOP(3,4)=TOP(4,2)
TOP(3,5)=TOP(4,3)
C
C Bottom roll point a global coordinates
C
   XAP=0.0
   YAP=(YBA-YTA)/2
   ZAP=(XBA-XBB)/2
   BOT(1,1)=XAP
   BOT(1,2)=YAP
   BOT(1,3)=ZAP

C
C Bottom roll point b global coordinates
C
   XBP=0.0
   YBP=(YBB-YTB)/2
   ZBP=(XBB-XBA)/2
   BOT(2,1)=XBP
   BOT(2,2)=YBP
   BOT(2,3)=ZBP

C
 DO 55 I=4,10000
C
READ(3,*,END=60)R
IF(R.GT.0.0)THEN
   READ(3,*)X,Y,Z
   READ(3,*)SA
   READ(3,*)EA
   BOTX(I,1)=R
BOTX(I,2) = X
BOTX(I,3) = Y
BOTX(I,4) = SA
BOTX(I,5) = EA
ELSE
READ(3,*)X1, Y1, Z1
READ(3,*)X, Y, Z
BOTX(I,1) = 0.0
BOTX(I,2) = X1
BOTX(I,3) = Y1
BOTX(I,4) = X
BOTX(I,5) = Y
ENDIF
55 CONTINUE
C
60 CONTINUE
C
CLOSE(UNIT=2)
CLOSE(UNIT=3)
C
IF(CLOCKBOT.GT.0.0) THEN
DO 124 I = 4, NBOT + 3
DO 125 J = 1, 5
BOT(I,J) = BOTX(NBOT + 7 - I, J)
125 CONTINUE
124 CONTINUE
DO 320 I = 4, NTOP + 3
IF(BOT(I,1).LE.0.0) THEN
X1 = BOT(I,2)
Y1 = BOT(I,3)
BOT(I,2) = BOT(I,4)
BOT(I,3) = BOT(I,5)
BOT(I,4) = X1
BOT(I,5) = Y1
ENDIF
320 CONTINUE
ELSE
DO 224 I = 4, NBOT + 3
DO 225 J = 1, 5
BOT(I,J) = BOTX(I,J)
225 CONTINUE
224 CONTINUE
ENDIF
C
Now we have to do something with the first points

\[
\begin{align*}
\text{BOT}(3,1) &= 0.0 \\
\text{BOT}(3,4) &= \text{BOT}(4,2) \\
\text{BOT}(3,5) &= \text{BOT}(4,3)
\end{align*}
\]

DO 126 I=3,NTOP+3
IF(TOP(I,1).GT.0.0)THEN
  R=TOP(I,1)
  X=TOP(I,2)
  Y=TOP(I,3)
  SA=TOP(I,4)
  EA=TOP(I,5)
  \text{TOP}(I,1) = 1.0
  \text{IF}(\text{SA} \leq \text{0.5*PI}) \text{THEN}
    \text{TOP}(I,2) = \text{YTA-Y-R*}\text{SIN}(\text{EA})
    \text{TOP}(I,3) = \text{X-XTA+R*}\text{COS}(\text{EA})
  \text{ELSE}
    \text{TOP}(I,2) = \text{YTA-Y-R*}\text{SIN}(\text{SA})
    \text{TOP}(I,3) = \text{X-XTA+R*}\text{COS}(\text{SA})
  \text{ENDIF}
  \text{TOP}(I,4) = \text{YTA-Y}
  \text{TOP}(I,5) = \text{X-XTA}
\text{ELSE}
  R=\text{TOP}(I,1)
  X=\text{TOP}(I,4)
  Y=\text{TOP}(I,5)
  \text{TOP}(I,4) = 0.0
  \text{TOP}(I,5) = 0.0
  \text{TOP}(I,1) = 0.0
  \text{TOP}(I,2) = \text{YTA-Y}
  \text{TOP}(I,3) = \text{X-XTA}
\text{ENDIF}
126 CONTINUE

DO 127 I=3,NBOT+3
IF(BOT(I,1).GT.0.0)THEN
  R=BOT(I,1)
  X=BOT(I,2)
  Y=BOT(I,3)
  SA=BOT(I,4)
  EA=BOT(I,5)
  \text{BOT}(I,1) = 1.0
IF(SA.GE.(0.5*PI)) THEN
  BOT(1,2) = Y - YBA + R*SIN(SA)
  BOT(1,3) = X - XBA + R*COS(SA)
ELSE
  BOT(1,2) = Y - YBA + R*SIN(EA)
  BOT(1,3) = X - XBA + R*COS(EA)
ENDIF
BOT(1,4) = Y - YBA
BOT(1,5) = X - XBA
ELSE
  R = BOT(I,1)
  X = BOT(I,4)
  Y = BOT(I,5)
  BOT(I,4) = 0.0
  BOT(I,5) = 0.0
  BOT(I,1) = 0.0
  BOT(I,2) = Y - YBA
  BOT(I,3) = X - XBA
ENDIF
127 CONTINUE

C
TRD = TOP(3,2)
BRD = BOT(3,2)
DO 80 I = 3, 100
  TRD = MAX(TRD, TOP(I,2))
  BRD = MAX(BRD, BOT(I,2))
80 CONTINUE

C
OPEN(UNIT=9, FILE='NEW.DAT', STATUS='UNKNOWN')
100 FORMAT(1P, E11.4, 1X, E11.4, 1X, E11.4, 1X, E11.4, 1X, E11.4)

C
CLOSE(UNIT=9)
RETURN
END
Appendix B1: Plain-Strain Rolling ABAQUS Input File

*HEADING, UNSYMM
2-D Rolling for Validation of Results
Roll diameter = .15875E+00 m
Roll speed = .19200E+02 RPM
Initial stock = .62740E-02 m
Roll gap = .53850E-02 m
Billet length = .25000E-01 m
Friction = .100
Reduction = 14.170 %
Material = ALUM
Young Modulus = .73084E+11
Poisson Ratio = .330
Strength coef. = .50300E+08
Strain Hard. = .260
*RESTART, WRITE, FREQUENCY=40
** Start Model Definition **
*N NODE, NSET=ROLL
9999, 00000E+00, 82067E-01
*N NODE, NSET=PUSH
8888, 33448E-01, 34507E-02
** Define nodes in the billet **
*N NODE
1, .54534E-02, 00000E+00
6, .84482E-02, 00000E+00
57, 33448E-01, 00000E+00
501, 54534E-02, 28547E-02
506, 84482E-02, 31370E-02
557, 33448E-01, 31370E-02
647, 28448E-01, 31370E-02
657, 33448E-01, 31370E-02
*N GEN, NSET=BCURV
1, 6
*N GEN, NSET=BLINE
6, 57
*N GEN, NSET=TCURV
501, 506
*N GEN, NSET=TLINE
506, 557
*N GEN, NSET=TOP2
647, 657
*N FILL, BIAS=1.5, NSET=STOCK
BCURV,TCURV, 5,100
*NSET,NSET=TOP1,GENERATE
  547, 557
*NSET,NSET=TOP,GENERATE
  501, 557
*NSET,NSET=FRONT,GENERATE
  1,501,100
*NSET,NSET=BOTTOM
BCURV,BLINE
*NSET,NSET=BACK,GENERATE
  57,557,100
*NSET,NSET=PERIM
BOTTOM,TOP,BACK,FRONT
** Generate Elements **
*ELEMENT,TYPE=CPE4R,ELSET=BILLET
  1,1,2,102,101
*ELGEN,ELSET=BILLET
  1, 56,1,1, 5,100,100
*ELEMENT,TYPE=IRS21
  9901, 501, 502,9999
  8801, 647, 648,8888
  8811, 657, 457,8888
  8802, 648, 649,8888
  8803, 649, 650,8888
  8804, 650, 651,8888
  8805, 651, 652,8888
  8806, 652, 653,8888
  8807, 653, 654,8888
  8808, 654, 655,8888
  8809, 655, 656,8888
  8810, 656, 657,8888
  8812, 457, 357,8888
  8813, 357, 257,8888
  8814, 257, 157,8888
  8815, 157, 57,8888
*ELSET,ELSET=FOLD,GENERATE
  8801,8815
*ELGEN,ELSET=TROLL
  9901, 56,1,1
** Define Rigid Surfaces **
*RIGID SURFACE,ELSET=TROLL,TYPE=SEGMENTS
START, .79375E-01, .82067E-01
CIRCL,  .00000E+00,  .26925E-02,  .00000E+00,  .82067E-01
CIRCL,  -.79375E-01,  .82067E-01,  .00000E+00,  .82067E-01
CIRCL,  .00000E+00,  .16144E+00,  .00000E+00,  .82067E-01
CIRCL,  .79375E-01,  .82067E-01,  .00000E+00,  .82067E-01
*RIGID SURFACE,ELSET=FOLD,TYP=SEGMENTS
START,  .33448E-01,  -.15000E-02
LINE,  .33448E-01,  .43918E-02
** Define frictional conditions **
*INTERFACE,ELSET=FOLD
*FRICITION
  1.E15,1.E15
*INTERFACE,ELSET=TROLL
*FRICITION
  .100,  .10060E+13,  .50300E+08
** Define Material Properties **
*SOLID SECTION,ELSET=BILLET,MATERIAL=ALUM
*MATERIAL,NAME=ALUM
*ELASTIC
  .7308E+11,  .330
*PLASTIC,HARD=ISO
  .50300E+08,  .000
  .60233E+08,  .050
  .66930E+08,  .100
  .72128E+08,  .150
  .76436E+08,  .200
  .80147E+08,  .250
  .83424E+08,  .300
  .86372E+08,  .350
  .89058E+08,  .400
  .91531E+08,  .450
  .93827E+08,  .500
  .95974E+08,  .550
  .97993E+08,  .600
  .99899E+08,  .650
  1.0171E+09,  .700
  1.0343E+09,  .750
  1.0507E+09,  .800
  1.0664E+09,  .850
  1.0815E+09,  .900
  1.0961E+09,  .950
  1.1101E+09,  1.000
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** Define Boundary Conditions **

*EQUATION

2
TOP2,1,1.0,TOP1,1,-1.0
2
TOP2,2,1.0,TOP1,2,-1.0

** Start Model Definition **

*STEP,INC=3000,CYCLE=15,SUBMAX,MONOTONIC,NLGEOM,AMP=RAMP

Push the billet slowly. Rolls are turning

*STATIC,PTOL=.50000E+02
.1000E-04, .9956E-01, .1000E-14
*FILE FORMAT, ASCII
*BOUNDARY
BOTTOM, 2
ROLL, 1, 2
PUSH, 1, 1, -.0040
PUSH, 2
PUSH, 6
ROLL, 6, 6, -.2002
*PRINT, CONTACT = NO, RESIDUAL = NO, FREQUENCY = 50
*EL FILE, ELSET = BILLET, FREQUENCY = 40
SINV, PE
*NODE FILE, NSET = STOCK, FREQUENCY = 50
U
*EL PRINT, ELSET = TROLL, FREQUENCY = 10
S11, S12
*EL FILE, ELSET = TROLL, FREQUENCY = 40
S
*NODE PRINT, NSET = PUSH, FREQUENCY = 40, SUMMARY = NO
COOR1, COOR2, U1, U2, RF1, RF2, RM3
*NODE PRINT, NSET = ROLL, FREQUENCY = 40, SUMMARY = NO
RF
*NODE PRINT, NSET = TOP, FREQUENCY = 40, SUMMARY = NO
COOR1, COOR2, U1, U2
*NODE FILE, NSET = PUSH, FREQUENCY = 1
RF
*NODE FILE, NSET = ROLL, FREQUENCY = 1
RF
*NODE PRINT, NSET = TOP, FREQUENCY = 40, SUMMARY = NO
COOR1, COOR2, U1, U2
*END STEP
Appendix B2: Case Study 5a ABAQUS Input File

*HEADING,UNSYMM
y5.inp  . 3-D Shape Rolling. R- W- T+ M+ F-
Maximum Roll Radius = 1.01600E-01 m
Roll Gap at Intersection = 3.21772E-02 m
Intersecting Roll Radius = 8.80514E-02 m
Roll Speed = 6.00000E+00 RPM
Initial Billet Thickness = 5.08000E-02 m
Initial Billet Width = 5.08000E-02 m
Initial Billet Length = 1.01600E-01 m
Friction = .700
Material File Name = AISI1045.MAT
Young Modulus = 2.10000E+11
Poisson Ratio = .300
Strength coefficient = 1.01970E+09
Strain Hardening coef. = .110
*RESTART,WRITE,FREQUENCY= 40
**  Start Model Definition **
*NODE,NSET=ROLL
99999, -1.27000E-05, 1.04140E-01, -5.54000E-02
*NODE,NSET=PUSH
88888, 1.41022E-01, 2.79400E-02, 0.00000E+00
** Define nodes in the billet **
*NODE
  1, 3.94089E-02, 0.00000E+00, 0.00000E+00
  41, 1.41009E-01, 0.00000E+00, 0.00000E+00
  501, 3.94089E-02, 2.54000E-02, 0.00000E+00
  541, 1.41009E-01, 2.54000E-02, 0.00000E+00
  5001, 3.94089E-02, 0.00000E+00, -2.54000E-02
  5041, 1.41009E-01, 0.00000E+00, -2.54000E-02
  5501, 3.94089E-02, 2.54000E-02, -2.54000E-02
  5541, 1.41009E-01, 2.54000E-02, -2.54000E-02
*NGEN,NSET=BLLINE
  1, 41
*NGEN,NSET=TLLINE
  501, 541
*NGEN,NSET=FRONTL
  1, 501,100
*NGEN,NSET=BACLKL
  41, 541,100
*NGEN,NSET=BRLINE
  5001,5041
*NGEN,NSET=TRLINE
5501,5541
*NGEN,NSET=FRONTR
5001,5501,100
*NGEN,NSET=BACKR
5041,5541,100
*NFILL,NSET=STOCKL
BLLINE,TLLINE, 5,100
*NFILL,NSET=STOCKR
BRLINE,TRLINE, 5,100
*NFILL,NSET=STOCK
STOCKL,STOCKR, 5,1000
*NFILL,NSET=BOTTOM
BLLINE,BRLINE, 5,1000
*NFILL,NSET=TOP
TLLINE,TRLINE, 5,1000
*NFILL,NSET=FRONT
FRONTL,FRONTR, 5,1000
*NFILL,NSET=BACK
BACKL,BACKR, 5,1000
*NSET,NSET=AREA
BOTTOM,STOCKL,STOCKR,TOP,FRONT,BACK

** Generate Elements **
*ELEMENT,TYPE=C3D8R,ELSET=BILLET
1,1001,1002,1102,1101,1,2,102,101
*ELGEN,ELSET=BILLET
1, 40,1,1, 5,100,100, 5,1000,1000
*ELEMENT,TYPE=IRS13
901, 501,99999
20001, 5001,99999
801, 541,88888
*ELGEN,ELSET=TRLL
901, 40,1,1,1,100,100, 6,1000,1000
*ELGEN,ELSET=SRLL
20001, 40,1,1,5,100,100, 1,1000,1000
*ELSET,ELSET=TROLL
TRLL,SRLL
*ELGEN,ELSET=FOLD
801,1,1,1, 6,-100,1, 6,1000,1000

** Define Rigid Surfaces **
*RIGID SURFACE,ELSET=TROLL,TYPE=AXISYMMETRIC
-1.27000E-05,1.04140E-01,-5.54000E-02,-1.27000E-05,1.04140E-01,5.54000E-02
START, 0.00000E+00, 1.10800E-01
LINE, 1.01600E-01, 1.10800E-01
LINE, 1.01600E-01, 9.58000E-02
CIRCL, 8.12799E-02, 5.54001E-02, 1.30808E-01, 5.57990E-02
CIRCL, 1.01600E-01, 1.49999E-02, 1.30808E-01, 5.50010E-02
LINE, 1.01600E-01, 0.00000E+00
LINE, 0.00000E+00, 0.00000E+00
*RIGID SURFACE,ELSET=FOLD,TYPE=CYLINDER
  1.41022E-01, 0.00000E+00, 5.08000E-03, 1.41022E-01, 2.54000E-02, 5.08000E-03
  1.41022E-01, 0.00000E+00, -3.04800E-02
START,-1.50000E-03, 0.00000E+00
LINE, 3.55600E-02, 0.00000E+00
** Define frictional conditions **
*INTERFACE,ELSET=FOLD
  1.79211E-05,1.0,0.0,0.0
*FRICTION
  1.E15,1.E15
*INTERFACE,ELSET=TRLL
  1.04904E-05,0.0,1.0,0.0
*FRICTION
  .700, 1.08715E+12, 6.93355E+08
*INTERFACE,ELSET=SRLL
  1.25885E-05,0.0,0.0,-1.0
*FRICTION
  .700, 1.08715E+12, 6.93355E+08
** Define Material Properties **
*SOLID SECTION,ELSET=BILLET,MATERIAL=AISI
*MATERIAL,NAME=AISI
*ELASTIC
  2.10000E+11,3.000E-01
*PLASTIC,HARD=ISO
  6.63110E+08, 0.000E+00
  7.91539E+08, 1.000E-01
  8.54251E+08, 2.000E-01
  8.93214E+08, 3.000E-01
  9.21932E+08, 4.000E-01
  9.44842E+08, 5.000E-01
  9.63982E+08, 6.000E-01
  9.80467E+08, 7.000E-01
  9.94975E+08, 8.000E-01
  1.00795E+09, 9.000E-01
  1.01970E+09, 1.000E+00
  1.03045E+09, 1.100E+00
  1.04036E+09, 1.200E+00
  1.04956E+09, 1.300E+00
  1.05815E+09, 1.400E+00
1.06621E+09, 1.500E+00
1.07381E+09, 1.600E+00
1.08099E+09, 1.700E+00
1.08781E+09, 1.800E+00
1.09430E+09, 1.900E+00
1.10049E+09, 2.000E+00
1.10641E+09, 2.100E+00
1.11209E+09, 2.200E+00
1.11754E+09, 2.300E+00
1.12278E+09, 2.400E+00
1.12784E+09, 2.500E+00
1.13271E+09, 2.600E+00
1.13742E+09, 2.700E+00
1.14198E+09, 2.800E+00
1.14640E+09, 2.900E+00
1.15068E+09, 3.000E+00
1.15484E+09, 3.100E+00
1.15888E+09, 3.200E+00
1.16281E+09, 3.300E+00
1.16664E+09, 3.400E+00
1.17036E+09, 3.500E+00
1.17399E+09, 3.600E+00
1.17754E+09, 3.700E+00
1.18100E+09, 3.800E+00
1.18438E+09, 3.900E+00
1.18768E+09, 4.000E+00
1.19091E+09, 4.100E+00
1.19407E+09, 4.200E+00
1.19716E+09, 4.300E+00
1.20020E+09, 4.400E+00
1.20317E+09, 4.500E+00
1.20608E+09, 4.600E+00
1.20894E+09, 4.700E+00
1.21174E+09, 4.800E+00
1.21449E+09, 4.900E+00

** Start History Definition **
*STEP,INC= 3000,CYCLE=15,SUBMAX,MONOTONIC,NLGEOM,AMP=RAMP
Push the billet slowly. Rolls are turning
*STATIC,PTOL= 2.03393E+03
  1.49588E-05, 1.49588E+00, 1.49588E-15
*FILE FORMAT,ASCII
*BOUNDARY
BOTTOM,2
STOCKL,3
ROLL, 1, 5
PUSH, 1, 1, -2.0690E-02
PUSH, 2, 6
ROLL, 6, 6, -9.3989E-01
*PRINT, CONTACT = NO, RESIDUAL = NO, FREQUENCY = 300
*EL FILE, ELSET = BILLET, FREQUENCY = 40
SINV, PE
*EL FILE, ELSET = TROLL, FREQUENCY = 40
S
*NODE FILE, NSET = AREA, FREQUENCY = 40
COORD
*NODE FILE, NSET = STOCK, FREQUENCY = 40
U
*NODE FILE, NSET = PUSH, FREQUENCY = 1
RF
*NODE FILE, NSET = ROLL, FREQUENCY = 1
RF
*NODE PRINT, NSET = AREA, FREQUENCY = 40
COORD3, COORD2
*NODE PRINT, NSET = PUSH, FREQUENCY = 10, SUMMARY = NO
COORD1, U1, RF1
*NODE PRINT, NSET = ROLL, FREQUENCY = 10, SUMMARY = NO
RF
*EL PRINT, ELSET = TROLL, FREQUENCY = 40
S11, S12, S13
*END STEP
Appendix B3: Case 8b ABAQUS Input File

*HEADING, UNSYMM
f100.inp  3-D Shape Rolling. First Pass. Origin + 7*delta
Maximum Roll Radius = 1.01600E-01 m
Roll Gap at Intersection = 3.01110E-02 m
Intersecting Roll Radius = 9.44075E-02 m
Roll Speed = 6.00000E+00 RPM
Initial Billet Thickness = 4.98800E-02 m
Initial Billet Width = 6.79750E-02 m
Initial Billet Length = 1.01600E-01 m
Friction = 0.800
Material File Name = AISI1020.MAT
Young Modulus = 2.10000E+11
Poisson Ratio = 0.300
Strength coefficient = 7.45320E+08
Strain Hardening coef. = 0.200
*RESTART, WRITE, FREQUENCY= 40
** Start Model Definition **
*NODE, NSET=ROLL
99999, -1.27000E-05, 1.09463E-01,-5.54000E-02
*NODE, NSET=PUSH
88888, 1.43668E-01, 2.74340E-02, 0.00000E+00
** Define nodes in the billet **
*NODE
  1, 4.20552E-02, 0.00000E+00, 0.00000E+00
  41, 1.43655E-01, 0.00000E+00, 0.00000E+00
  401, 4.20552E-02, 2.49400E-02, 0.00000E+00
  441, 1.43655E-01, 2.49400E-02, 0.00000E+00
  6001, 4.20552E-02, 0.00000E+00,-3.39875E-02
  6041, 1.43655E-01, 0.00000E+00,-3.39875E-02
  6401, 4.20552E-02, 2.49400E-02,-3.39875E-02
  6441, 1.43655E-01, 2.49400E-02,-3.39875E-02
*NGEN, NSET=BLINE
  1, 41
*NGEN, NSET=TLINE
  401, 441
*NGEN, NSET=FRONTL
  1, 401, 100
*NGEN, NSET=BACL
  41, 441, 100
*NGEN, NSET=BRLINE
  6001, 6041
*NGEN,NSET=TRLINE
6401,6441
*NGEN,NSET=FRONTR
6001,6401,100
*NGEN,NSET=BACKR
6041,6441,100
*NFILL,NSET=STOCKL
BLLINE,TLLINE, 4,100
*NFILL,NSET=STOCKR
BRLINE,TRLINE, 4,100
*NFILL,NSET=STOCK
STOCKL,STOCKR, 6,1000
*NFILL,NSET=BOTTOM
BLLINE,BRLINE, 6,1000
*NFILL,NSET=TOP
TLLINE,TRLINE, 6,1000
*NFILL,NSET=FRONT
FRONTL,FRONTR, 6,1000
*NFILL,NSET=BACK
BACKL,BACKR, 6,1000
*NSET,NSET=AREA
BOTTOM,STOCKL,STOCKR,TOP,FRONT,BACK
** Generate Elements **
*ELEMENT,TYPE=C3D8R,ELSET=BILLET
1,1001,1002,1102,1101,1,2,102,101
*ELGEN,ELSET=BILLET
1, 40,1,1 ,4,100,100, 6,1000,1000
*ELEMENT,TYPE=IRS13
 901, 401,99999
20001, 6001,99999
 801, 441,88888
*ELGEN,ELSET=TRLL
   901, 40,1,1,1,100,100, 7,1000,1000
*ELGEN,ELSET=SRLL
20001, 40,1,1,4,100,100, 1,1000,1000
*ELSET,ELSET=TROLL
TRLL,SRLL
*ELGEN,ELSET=FOLD
  801,1,1,1, 5,-100,1, 7,1000,1000
** Define Rigid Surfaces **
*RIGID SURFACE,ELSET=TROLL,TYPE=AXISYMMETRIC
-1.27000E-05, 1.09463E-01,-5.54000E-02,-1.27000E-05, 1.09463E-01,5.54000E-02
START, 0.00000E+00, 1.10800E-01
LINE, 1.01600E-01, 1.10800E-01
LINE, 1.01600E-01, 9.58000E-02
CIRCL, 8.12804E-02, 5.54000E-02, 1.30809E-01, 5.57989E-02
CIRCL, 1.01600E-01, 1.50000E-02, 1.30809E-01, 5.50011E-02
LINE, 1.01600E-01, 0.00000E+00
LINE, 0.00000E+00, 0.00000E+00
*RIGID SURFACE,ELSET=FOLD,TYPE=CYLINDER
  1.43668E-01, 0.00000E+00, 6.79750E-03, 1.43668E-01, 2.49400E-02, 6.79750E-03
  1.43668E-01, 0.00000E+00, -4.07850E-02
START,-1.50000E-03, 0.00000E+00
LINE, 3.49160E-02, 0.00000E+00
** Define frictional conditions **
*INTERFACE,ELSET=FOLD
  2.42185E-05,1.0,0.0,0.0
*FRICITION
  1.E15,1.E15
*INTERFACE,ELSET=TRLL
  1.20318E-05,0.0,1.0,0.0
*FRICITION
  .800, 8.28428E+11, 3.69630E+08
*INTERFACE,ELSET=SRLL
  1.54506E-05,0.0,0.0,-1.0
*FRICITION
  .800, 8.28428E+11, 3.69630E+08
** Define Material Properties **
*SOLID SECTION,ELSET=BILLET,MATERIAL=AISI
*MATERIAL,NAME=AISI
*ELASTIC
  2.10000E+11,3.00E-01
*PLASTIC,HARD=ISO
  3.40839E+08,  0.000E+00
  4.70265E+08,  1.000E-01
  5.40193E+08,  2.000E-01
  5.85824E+08,  3.000E-01
  6.20519E+08,  4.000E-01
  6.48839E+08,  5.000E-01
  6.72935E+08,  6.000E-01
  6.94005E+08,  7.000E-01
  7.12789E+08,  8.000E-01
  7.29779E+08,  9.000E-01
  7.45320E+08,  1.000E+00
  7.59664E+08,  1.100E+00
  7.72999E+08,  1.200E+00
  7.85473E+08,  1.300E+00
  7.97202E+08,  1.400E+00
8.08279E+08, 1.500E+00
8.18779E+08, 1.600E+00
8.28767E+08, 1.700E+00
8.38296E+08, 1.800E+00
8.47410E+08, 1.900E+00
8.56148E+08, 2.000E+00
8.64543E+08, 2.100E+00
8.72624E+08, 2.200E+00
8.80417E+08, 2.300E+00
8.87943E+08, 2.400E+00
8.95222E+08, 2.500E+00
9.02272E+08, 2.600E+00
9.09108E+08, 2.700E+00
9.15745E+08, 2.800E+00
9.22194E+08, 2.900E+00
9.28468E+08, 3.000E+00
9.34577E+08, 3.100E+00
9.40530E+08, 3.200E+00
9.46336E+08, 3.300E+00
9.52003E+08, 3.400E+00
9.57539E+08, 3.500E+00
9.62949E+08, 3.600E+00
9.68240E+08, 3.700E+00
9.73418E+08, 3.800E+00
9.78488E+08, 3.900E+00
9.83456E+08, 4.000E+00
9.88324E+08, 4.100E+00
9.93099E+08, 4.200E+00
9.97784E+08, 4.300E+00
1.00238E+09, 4.400E+00
1.00690E+09, 4.500E+00
1.01133E+09, 4.600E+00
1.01569E+09, 4.700E+00
1.01998E+09, 4.800E+00
1.02419E+09, 4.900E+00

** Start History Definition **
*STEP,INC= 3000,CYCLE=15,SUBMAX,MONOTONIC,NLGEOM,AMP=RAMP
Push the billet slowly. Rolls are turning
*STATIC,PTOL= 2.13676E+03
  1.48886E-05, 1.48886E+00, 1.48886E-15
*FILE FORMAT,ASCII
*BOUNDARY
BOTTOM,2
STOCKL,3
ROLL,1,5
PUSH,1,1,-2.2079E-02
PUSH,2,6
ROLL,6,6,-9.3548E-01
*PRINT,CONTACT=NO,RESIDUAL=NO,FREQUENCY=300
*EL FILE,ELSET=BILLET,FREQUENCY=40
SINV,PE
*EL FILE,ELSET=TROLL,FREQUENCY=40
S
*NODE FILE,NSET=AREA,FREQUENCY=40
COORD
*NODE FILE,NSET=STOCK,FREQUENCY=40
U
*NODE FILE,NSET=PUSH,FREQUENCY=1
RF
*NODE FILE,NSET=ROLL,FREQUENCY=1
RF
*NODE PRINT,NSET=AREA,FREQUENCY=40
COORD3,COORD2
*NODE PRINT,NSET=PUSH,FREQUENCY=10,SUMMARY=NO
COORD1,U1,RF1
*NODE PRINT,NSET=ROLL,FREQUENCY=10,SUMMARY=NO
RF
*EL PRINT,ELSET=TROLL,FREQUENCY=40
S11,S12,S13
*END STEP

*HEADING,UNSYMM
f102.inp. 3-D Shape Rolling. Second Pass. Origin + 7*delta
Maximum Roll Radius = 1.01600E-01 m
Roll Gap at Intersection = 3.01110E-02 m
Intersecting Roll Radius = 9.44075E-02 m
Roll Speed = 6.00000E+00 RPM
Initial Billet Thickness = 4.98800E-02 m
Initial Billet Width = 6.79750E-02 m
Initial Billet Length = 1.01600E-01 m
Friction = .800
Material File Name = AISI1020.MAT
Young Modulus = 2.10000E+11
Poisson Ratio = .300
Strength coefficient = 7.45320E+08
Strain Hardening coef. = .200
*RESTART,READ,STEP=1,INCREMENT=169,WRITE,FREQUENCY=40,END STEP
** Start History Definition **
*STEP,INC= 3000,CYCLE=15,SUBMAX,MONOTONIC,NLGEOM,AMP=RAMP
Move push die back. Move Top roll up without rotating it.
*STATIC,PTOL= 2.13676E+03
  1.48886E-05, 1.0, 1.48886E-15
*FILE FORMAT,ASCII
*BOUNDARY,OP=NEW
BOTTOM,2
STOCKL,3
ROLL,1,1
ROLL,2,2,9.8849E-03
ROLL,3,5
PUSH,1,1,8.9840E-03
PUSH,2,6
ROLL,6,6,-9.3548E-01
*PRINT,CONTACT=NO,RESIDUAL=NO,FREQUENCY=300
*EL FILE,ELSET=BILLET,FREQUENCY= 40
SINV,PE
*EL FILE,ELSET=TROLL,FREQUENCY= 40
S
*NODE FILE,NSET=AREA,FREQUENCY= 40
COORD
*NODE FILE,NSET=STOCK,FREQUENCY= 40
U
*NODE FILE,NSET=PUSH,FREQUENCY= 1
RF
*NODE FILE,NSET=ROLL,FREQUENCY= 1
RF
*NODE PRINT,NSET=AREA,FREQUENCY= 40
COORD3,COORD2
*NODE PRINT,NSET=PUSH,FREQUENCY= 10,SUMMARY=NO
COORD1,U1,RF1
*NODE PRINT,NSET=ROLL,FREQUENCY= 10,SUMMARY=NO
RF
*EL PRINT,ELSET=TROLL,FREQUENCY= 40
S11,S12,S13
*END STEP
** Continue history definition
*STEP,INC= 3000,CYCLE=15,SUBMAX,MONOTONIC,NLGEOM,AMP=RAMP
Move billet back. Rotate top roll back.
*STATIC,PTOL= 2.13676E+03
  1.48886E-05, 1.0, 1.48886E-15
*FILE FORMAT,ASCII
*BOUNDARY,OP=NEW
BACK,1,1,8.9840E-03
BOTTOM,2
STOCKL,3
ROLL,1,1
ROLL,2,2,9.8849E-03
ROLL,3,5
PUSH,1,1,8.9840E-03
PUSH,2,6
ROLL,6,6
*PRINT,CONTACT=NO,RESIDUAL=NO,FREQUENCY=300
*EL FILE,ELSET=BILLET,FREQUENCY= 40
SINV,PE
*EL FILE,ELSET=TROLL,FREQUENCY= 40
S
*NODE FILE,NSET=AREA,FREQUENCY= 40
COORD
*NODE FILE,NSET=STOCK,FREQUENCY= 40
U
*NODE FILE,NSET=PUSH,FREQUENCY= 1
RF
*NODE FILE,NSET=ROLL,FREQUENCY= 1
RF
*NODE PRINT,NSET=AREA,FREQUENCY= 40
COORD3,COORD2
*NODE PRINT,NSET=PUSH,FREQUENCY= 10,SUMMARY=NO
COORD1,U1,RF1
*NODE PRINT,NSET=ROLL,FREQUENCY= 10,SUMMARY=NO
RF
*EL PRINT,ELSET=TROLL,FREQUENCY= 40
S11,S12,S13
*END STEP
** Continue history definition
*STEP,INC= 3000,CYCLE=15,SUBMAX,MONOTONIC,NLGEOM,AMP=RAMP
Move roll down. Release movement from the billet.
*STATIC,PTOL= 2.13676E+03
1.48886E-05, 1.0, 1.48886E-15
*FILE FORMAT,ASCII
*BOUNDARY,OP=NEW
BOTTOM,2
STOCKL,3
ROLL,1,1
ROLL,2,2,-5.3226E-3
ROLL,3,5
PUSH,1,1,8.9840E-03
PUSH,2,6
ROLL, 6, 6
*PRINT, CONTACT=NO, RESIDUAL=NO, FREQUENCY=300
*EL FILE, ELSET=BILLET, FREQUENCY= 40
SINV, PE
*EL FILE, ELSET=TROLL, FREQUENCY= 40
S
*NODE FILE, NSET=AREA, FREQUENCY= 40
COORD
*NODE FILE, NSET=STOCK, FREQUENCY= 40
U
*NODE FILE, NSET=PUSH, FREQUENCY= 1
RF
*NODE FILE, NSET=ROLL, FREQUENCY= 1
RF
*NODE PRINT, NSET=AREA, FREQUENCY= 40
COORD3, COOR2
*NODE PRINT, NSET=PUSH, FREQUENCY= 10, SUMMARY=NO
COORD1, U1, RF1
*NODE PRINT, NSET=ROLL, FREQUENCY= 10, SUMMARY=NO
RF
*EL PRINT, ELSET=TROLL, FREQUENCY= 40
S11, S12, S13
*END STEP
*STEP, INC= 3000, CYCLE=15, SUBMAX, MONOTONIC, NLGEOM, AMP=RAMP
Push the billet slowly. Rolls are turning
*STATIC, PTOL= 2.13676E+03
1.48886E-05, 1.48886E+00, 1.48886E-15
*FILE FORMAT, ASCII
*BOUNDARY, OP=NEW
BOTTOM, 2
STOCKL, 3
ROLL, 1, 5
PUSH, 1, 1, -2.2079E-02
PUSH, 2, 6
ROLL, 6, 6, -9.3548E-01
*PRINT, CONTACT=NO, RESIDUAL=NO, FREQUENCY=300
*EL FILE, ELSET=BILLET, FREQUENCY= 40
SINV, PE
*EL FILE, ELSET=TROLL, FREQUENCY= 40
S
*NODE FILE, NSET=AREA, FREQUENCY= 40
COORD
*NODE FILE, NSET=STOCK, FREQUENCY= 40
U
*NODE FILE,NSET=PUSH,FREQUENCY= 1
  RF
*NODE FILE,NSET=ROLL,FREQUENCY= 1
  RF
*NODE PRINT,NSET=AREA,FREQUENCY= 40
  COOR3,COOR2
*NODE PRINT,NSET=PUSH,FREQUENCY= 10,SUMMARY=NO
  COOR1,U1,RF1
*NODE PRINT,NSET=ROLL,FREQUENCY= 10,SUMMARY=NO
  RF
*EL PRINT,ELSET=TROLL,FREQUENCY= 40
  S11,S12,S13
*END STEP